Final Report for
United States Department of Energy

Low Speed Technology for Small Turbine Development
Reaction Injection Molded 7.5 Meter Wind Turbine Blade
December 21, 2007

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Dedication

The surviving members of the project team dedicate this report to the memory of

Dr. Forrest (Woody) Stoddard

For the life he devoted to the cause, we—and indeed the entire Wind Industry—owe Woody a debt that can never be repaid. Woody's brilliant engineering insight, limitless energy, inspiring enthusiasm, and patient skill as a teacher have changed our lives, the energy economy of the society in which we live, and the very landscape of our planet. Without a doubt, Woody left this world in far better shape than he found it.

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David M. Wright

Acknowledgements:

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The greatest level of appreciation is due to Dr. Forrest L. ('Woody') Stoddard who, as Principal Investigator, would have completed this final analysis and report had he lived. It fell to me to write the report but I could not have done it without Woody's expertise, experience, guidance and advice over the course of the project and the enormous amount of work that he accomplished on the project before his death in January 2007. He assembled the principals, envisioned the scope of the project and oversaw the work through to the last stages.

In addition, I wish to thank my other colleagues in the project, especially Louis J. Manfredi of LJM Consulting, Amherst, Massachusetts, for his work on the project and for his support, suggestions and helpful criticism in the writing of this report.

I also wish to thank the staff of the National Renewable Energy Laboratory. Many on the staff have provided direct or indirect contributions, but I am happy to single out Dr. James Tangler (emeritus) and Trudy Forsyth for their direct technical assistance and moral support in the project.

The Blade Group at Composite Engineering, Inc., headed by Woody Stoddard, served as the umbrella organization, providing administrative and technical support. The Industrial Partners mentioned below provided guidance, technical support and encouragement throughout this project. Without their generous contributions the project would not have been possible. Particular thanks are due to Mike Dellapia and Danny Notarnicola of Art Mold Corp, without whose generous support and dedicated hard work this project could never have been accomplished. Steve Ettore of GI Plastics and later of Paramont Manufacturing LLC made possible the successful transition from Polyurethane to DCPD. Readers of this report owe a debt of gratitude to Kathryn A. Wright of SweetBriar, Springfield, Massachusetts, for the excellent editing and I am indebted to her for her continuing support and encouragement throughout the project.

Contact information is provided in the appendix.

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A Project to Develop a Reaction Injection Molded 7.5 Meter Wind Turbine Blade

1. PROJECT KEY SUCCESSES

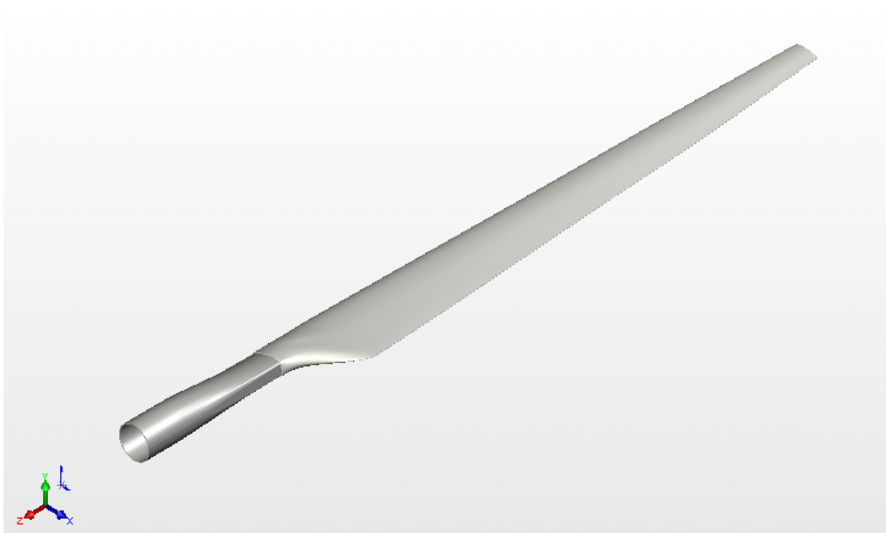
We proved it is possible to manufacture a wind turbine blade that is inexpensive, accurately shaped and consistent by utilizing modern techniques of mass production in high volume. We have demonstrated that such a blade can in fact be manufactured at very high rates of production and for very reasonable costs using the Reaction Injection Molding process in very large, temperature controlled matched dyes machined from aluminum blocks.

In the process of developing the blades we were able to automate much of the process of generating the blade geometry. We designed molds to produce upper and lower blade skins that can be assembled precisely and accurately because of consistent features that interlock to control the position of the skins relative to one another and to the spar. By controlling the blade assembly, these interlocking features allow simplification of assembly fixtures thereby accelerating the process and reducing the cost while leading to more consistently accurate blades. The interlocking features also control the bond line dimensions assuring dependable long-term adhesion of the bonded parts.

We established that a long, thin-walled part like a wind turbine blade skin can be molded in a thermosetting plastic. (Prior to this project molded blades had been limited to use on small wind turbines.) We have shown that the resulting molded parts have high quality consistent surfaces that require very little secondary finishing at the blade's leading and trailing edges.

2. Project Objective

An optimized small turbine blade (7.5m radius) will be designed and molded with the RIM process for mass production. The intended market is for generic three-bladed wind turbines, 100 kilowatts or less, for grid-assist end users with rural and semi-rural sites having IEC Class 3-4 wind regimes.



An Early Blade and Spar Design

3. Background

Project work is to design and build a RIM (reaction-injection molded polymer) 7.5m wind turbine blade suitable for the farm/ranch market in the US Great Plains, or low-to-moderate wind sites. This blade will have substantial performance improvements over, and be cheaper than, present-day 7.5m blades. This is made possible by the injection-molding process, which yields high repeatability, accurate geometry and weights, and low cost in production quantities. No wind turbine blade in the 7.5m or greater size has used this process. The blade design chosen uses a RIM skin bonded to a braided infused carbon fiber/epoxy spar. This approach is attractive to present users of wind turbine blades in the 5-10m sizes. These include rebladeing California wind farms, refurbishing used turbines for the Midwest farm market, and other manufacturers introducing new turbines in this size range.

Vestas V-15 w/ SERI Blades

California Wind Farm Turbines w/ Aerostar Blades

4. Project Summary

An optimized small turbine blade (7.5m radius) was designed and a partial section molded with the RIM process for mass production. The intended market is for generic three-bladed wind turbines, 100 kilowatts or less, for grid-assist end users with rural and semi-rural sites having IEC Class 3-4 wind regimes. During the course of the project the target turbine(s) changed several times. All the candidates were in the 100kW or lower class. Marketing studies and field surveys done in parallel with the project indicated that there is a strong market for blades of this size, both in the California replacement market and in the Midwestern farm market. These studies also indicated that the larger 19-meter machines while fewer in number would be the preferred candidates for blade replacement. The larger machines generally have lower maintenance costs and higher output which gives rehabilitating them a better return. The group realized that our method of blade

construction would allow us to mold the flight surfaces and then mount them on any of a number of spars so that a variety of turbines could be served by the same very expensive machined aluminum skin molds, with the obvious improvement in the economics of the proposition.
A business plan prepared early in the project concluded that the business model was marginal if based solely on replacing blades for the existing 15- through 19-meter wind turbines in California, but that if one expanded the market to include new wind turbines in the Midwest the plan became very attractive. While the specifics of the plan have changed the underlying strategies are sound.

The Phoenix SERI airfoil blade built and tested under a NREL contract was used as the baseline along with the Standard Aerostar blade commonly used on a large number of the 15- and 19-meter Danish machines in the California wind fields.

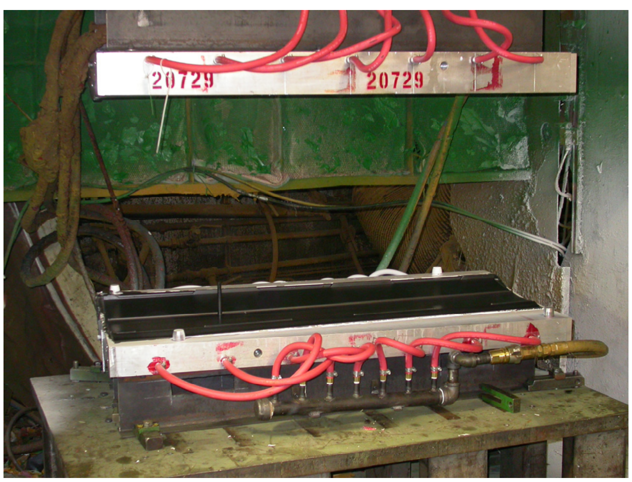
Phoenix and Aerostar Blades Being Tested Side by Side, Tehachapi, CA

5. Material Properties and Trial Part Testing

During the initial period and to a lesser extent throughout the remainder of the grant term the team reviewed literature and specification sheets for materials that could be utilized in the manufacture of wind turbine blades. Our efforts concentrated on materials from which to make the blade skins. We felt that the carbon fiber epoxy spar, with which Composite Engineering has had great success, was the clear choice for the load bearing function. The review began with materials suitable for all the processes we had initially considered to reassure the team that the chosen method of Reaction Injection Molding continued to be the wise choice. Concluding that we were on the right path we began examining the materials suitable for RIM, a much smaller list. Three materials worked their way to the top of the list; two polyurethane products (PU) and a DCPD material remained. The PU materials of interest are divided into groups, a structural-foam and a solid product. The solid PU has a slight edge because of its slightly higher modulus at similar yields; however it has a higher viscosity and is a bit more reactive, that is to say it is harder to fill long cavities and one has less time to accomplish the fill. The dicyclopentadiene (DCPD) material fell by the wayside for a couple of reasons, one a misunderstanding and the other a legitimate concern. GI Plastek, one of our industry partners had the facility where we planned to mold the skins. They preferred to run PU manufactured by Bayer Corp., another partner that manufactured only PU, so we believed that DCPD could not be bonded to. We later learned than while DCPD did not adhere to other materials well it could be bonded to once the surface had oxidized. Further, there are procedures that result in excellent bonds using a broad range of adhesives.

On the first attempt the engineers at GI Plastek were reluctant to mold the skins with a tapering wall thickness due to material flow concerns, so the test section was made with a constant wall thickness throughout.

Initially a scale model of the blade was planned to demonstrate the feasibility of the approach. After examining the cost to produce a scale model and realizing a scale model would not resolve any of the major concerns, it was decided to proceed with a 58-inch long section of the mid span of the blade mold as the first section of the planned 3-section mold. The completed mid-section mold segments were transported to GI Plastek's facility for a successful molding trial. The success of the trial and the properties of the resultant parts gave the team considerable confidence that we were on the right track both in the design of the skin sections and the choice of materials. There were some concerns about wear at the gate, which could lead to washout, and distortion of the flight surfaces and that the injection pressure was higher than anticipated. These moldings were assembled into a mocked up blade for display in a Poster Session at the 2005 AWEA Conference.



Mold Trial At GI Plastek

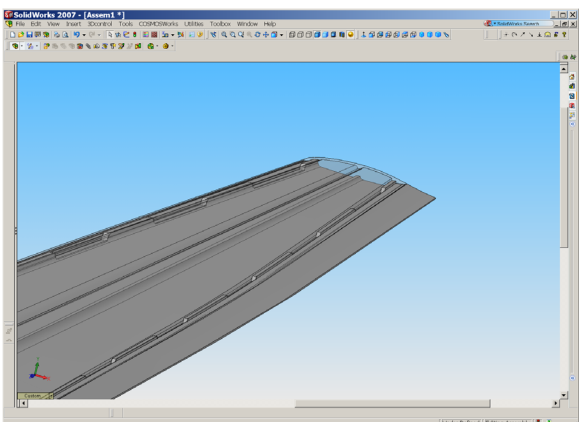
Woody Stoddard Examining The Skins

6. Blade Aerodynamics

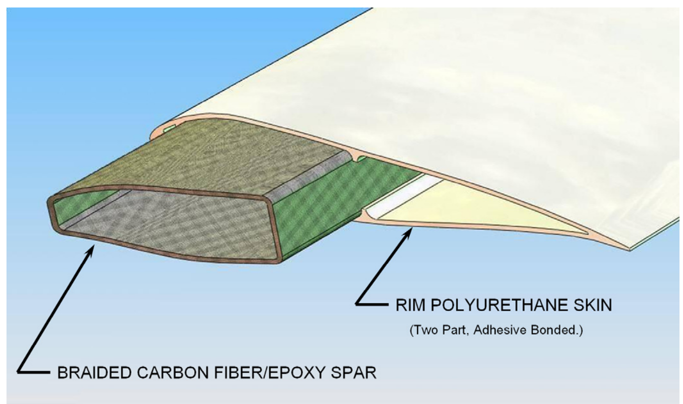
Because the focus of the grant is to evaluate new and improved methods of manufacture we decided to spend only a small part of our resources on aerodynamic analysis and optimization. The preliminary studies concentrated on loads rather than performance. The plan form, twist and chord distribution chosen are a simplification of design of the Phoenix SERI blade. The aerodynamic center of the airfoils was aligned with the centerline of the hub so that, if a pitching hub were used, the pitching moment of the airfoils would rotate the blades toward feather. Early studies suggested that if the blade were designed as a 9m blade and truncated at the root to create a 7.5m blade the output and annual production would fall between the Aero Star and the Phoenix blades with performance just slightly below the latter. Later studies indicated that the blade could be extended to 10m and would have more than acceptable performance. The extended length studies were the result of our realization that the molds we were building could be modified so that a family of blades could be molded by building the mold in segments so that by varying the number of segments used we could vary the overall blade length and that by matching the spar to a specific turbine we could extend the utility of the blade molds to cover most of the existing turbines and could provide blades for new designs as well.

7. Blade Structural Design

The design of the blade calls for a strong rigid spar that will carry the major flap, lead-lag and torque loads; the flight surfaces will only be required to transmit the aerodynamic loads to the spar. The design will allow the skins to be light and flexible and thereby able to shed peak loads. The skins will have molded-in features to facilitate self-alignment of the blade halves and to realize a controlled, uniform bond line.



Blade Alignment Features



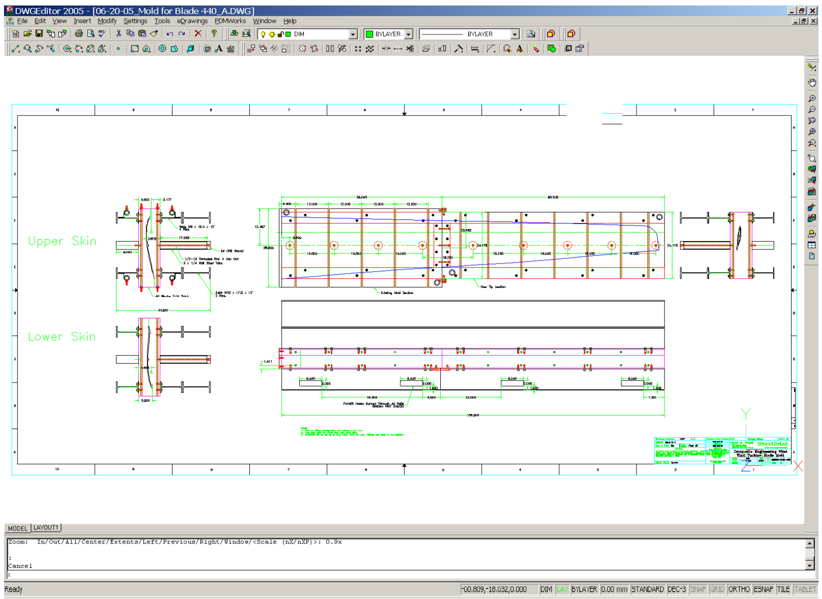
Strong Rigid Spar with Compliant Skins

The design of the spar was planned for the late stages of the project and in fact was not completed.

The design of the two skins was completed and a pair of machined aluminum molds was designed. The design was modified during the course of the project to reduce the cost to fit within a revised budget. A preliminary spar design and analysis indicated that the depth of the spar at some critical places would not be sufficient if we used a constant wall thickness as was done in the test section. To address the deficiency without compromising the aerodynamic design the thickness of the skins was changed from a constant thickness to a tapering thickness. The modification to the skin design and completed mold sections consumed considerably more time and resources than had been planned or budgeted.

8. Blade Tooling Design and Fabrication

During the project a number of tooling approaches were considered and pursued. The initial design concept called for two conventional RIM molds that could be operated either as freestanding self-clamped molds or as press mounted molds. Quotations for these molds were sought; however the responses proved much higher than our budget had anticipated. The team developed a concept of molds in which the cavity side which forms the actual flight surfaces of the skins would be machined from aluminum in a conventional manner and the core side of the molds which form the less critical interior surfaces would be created by developing an offset surface on the machined cavities, then hand laying up an FRP core. The combination approach was abandoned after cost studies proved that this approach was actually more expensive than an all machined approach. The high cost was driven by the labor cost for the modeling and hand lay-up and the cost and difficulty of creating the interlocking details planned.



Screen shot of mold design

Art Mold Corp of Roselle New Jersey joined the team as an industry partner and agreed to fabricate molds for a truncated version of the blade for a cost that we were able to fit into our budget. The molds will form the more critical outer section of the blade and the tip and inner "cuff" would be hand laid up over foam cores.

A concept was developed that will allow the molds to be used to manufacture blades in a range of lengths. The length of the blade can be increased by adding additional mold sections near the hub. By utilizing a combination of spar lengths and skin lengths the majority of existing turbines can be provided with new blades that will increase the annual production of the turbines while reducing the peak loads and thus annual maintence costs.

The results from the first molding trial suggested we would need to shift the gate from the middle of the blade to an edge. To help us choose an appropriate gate location and to confirm fill and pressure requirements Bayer Corp performed a series of flow simulation studies which indicated that we could inject the material into the trailing edge of the blade at a point about 0.3r along the blade but that the pressure required would be too high for the clamping methods we were considering.

Fabrication of the molds took a substantial amount more time than any of the group anticipated. During the mold build the GI Plastek facility that was designated to support the team and mold the parts was sold and the new owner was not interested in providing any further support. Steve Ettore, our sales contact at GI, returned to Paramont Manufacturing in Virginia and offered to provide support similar to that which GI had offered. The molding material for the parts to be molded at Paramont would be DCPD. The switch proved to be a major benefit as Metton DCPD has a much lower viscosity and a longer flow life than the Bayer PU we were using. The mold was completed and a molding trial held at Paramont's facility. 12 sets of upper and lower skins were successfully molded and returned to Composite Engineering's facility. The trial exceeded our expectations. The process was able to mold fully filled parts by the second shot and we had QC accepted parts by the fourth shot on the upper skin and the second shot on the lower. The cycle time was half of what was planned in spite of the awkward working conditions and having to fasten and unfasten the many clamps and open and close the molds with an overhead crane. Production rates of over 150 skins a day would present no significant problems. All of the production and planning personnel agreed that molding a blade skin twice the length of these test blades would not be a problem.

Mold Trial At Paramont

9. Root Transition Designed

A casting was designed to serve as the transition from the hub of the turbine to the spar. This casting was to adapt the spar to an AOC 15-50 turbine that would serve as the test bed at Princeton MA and later at Bushland TX.

The Root Transition Foundry Pattern

A Casting Emerges From The Sand

The arrangement with the Princeton utility did not work out and testing was to be done at the USDA facility at Bushland TX by Stoddard. Woody's untimely passing on January 25, 2007 put an end to that plan. The root transitions were cast but were not machined and are located at Composite Engineering. The molds are located at Paramont Manufacturing, the foundry pattern and core box are at the pattern makers awaiting return to Composite Engineering.

10. Field Test Results (if testing carried out)

Further funding from DoE is not available and our Industry Partners have chosen not to support a testing program. No field-testing will be done.

Should further funding become available Composite Engineering has several sets of skins, which could become candidates for testing to confirm the anticipated physical properties of the skins. The skins could also be assembled into blades for strength and flight evaluation. There are still open questions related to the mismatch of engineering modulus, the mismatched coefficients of thermal expansion and long term fatigue that could be resolved by bench testing these samples.

11. Publications and Presentations

Three team members gave presentations at the AWEA Conference in 2005. Manfredi (Automated Turbine Blade Lofting Based on a Commercial 3D CAD Application) and Wright (RIM for Mass-Produced High Quality Wind Turbine Blade) gave presentations in the Technical Track and Stoddard presented in the Poster Section (The KARATE Rotor: A Tuned, Self-Aligning, Self Governing Rotor for a 50-100kW Farm Wind Turbine). Manfredi and Wright's presentation and papers are available on the CDs of the conference through AWEA.

At Bayer's request, Stoddard attended the 2005 American Composite Manufacturer's Association national conference in Cleveland, OH, to present RIM blade samples, make informal presentations and answer questions about wind turbines and the RIM blade project. Additional discussions were held during the conference with other polymer manufacturers and tooling companies. Many composites companies were advertising wind turbines as a growing market and product line. Some blade sections were on display, including the CEI RIM blade.

12. Patents:

No patents have been identified or applied during the grant period.

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Appendix A

Acknowledgment: "This material is based upon work supported by the Department of Energy under Grant Number DE-FG36-04GO14256."

AUTOMATED BLADE LOFTING BASED ON COMMERCIAL 3D CAD APPLICATION

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Presented to AWEA Annual Conference May 16, 2005

ABSTRACT

Turbine blades have a complex shape driven by aerodynamic, structural, manufacturability and aesthetic requirements. Prior work depended on manual lofting or task-specific computer codes. These approaches have serious shortcomings. Each iteration of manual lofting is so time consuming that the design process may stop before the design is optimized. Using task-specific codes, the ability to visually evaluate the form is limited.

An automated process for defining, refining, and visualizing wind turbine blade geometry is described. Current work is in the context of a 7.5 meter blade using reaction injection molded skins and a carbon fiber/epoxy spar. The process described is applicable to other sizes and manufacturing technologies.

The process uses a commercial 3D CAD package (SolidWorks). A macro program reads chord, twist, section and internal geometry for each spanwise station from a spreadsheeet and generates a full 3D model of the blade geometry in a matter of minutes, allowing quick iteration and detailed design visualization.

The method defines the entire geometry of the blade. The outboard portion is governed primarily by aerodynamic considerations, while the inboard is dominated by structural, manufacturing and aesthetic issues. Handling the design in a single process avoids undesirable discontinuities in this transition.

The process fully defines the internal geometry of the blade, including spar geometry, skin thickness, and geometry of longitudinal ribs which locate the skin on the spar. By defining the entire blade in a single design document (the solid model) trade-offs between various requirements are more easily explored.

INTRODUCTION:

We have developed an automated lofting technique based on a commercial three dimensional solids modeling package (SolidWorks). The technique takes advantage of the package's macro-programming capabilities to generate a blade design document (solid model) which defines the blade internally and externally in a complete, mathematically rigorous, and easily visualized manner. The current version of the technique generates a completely defined shape in a largely automatic manner.

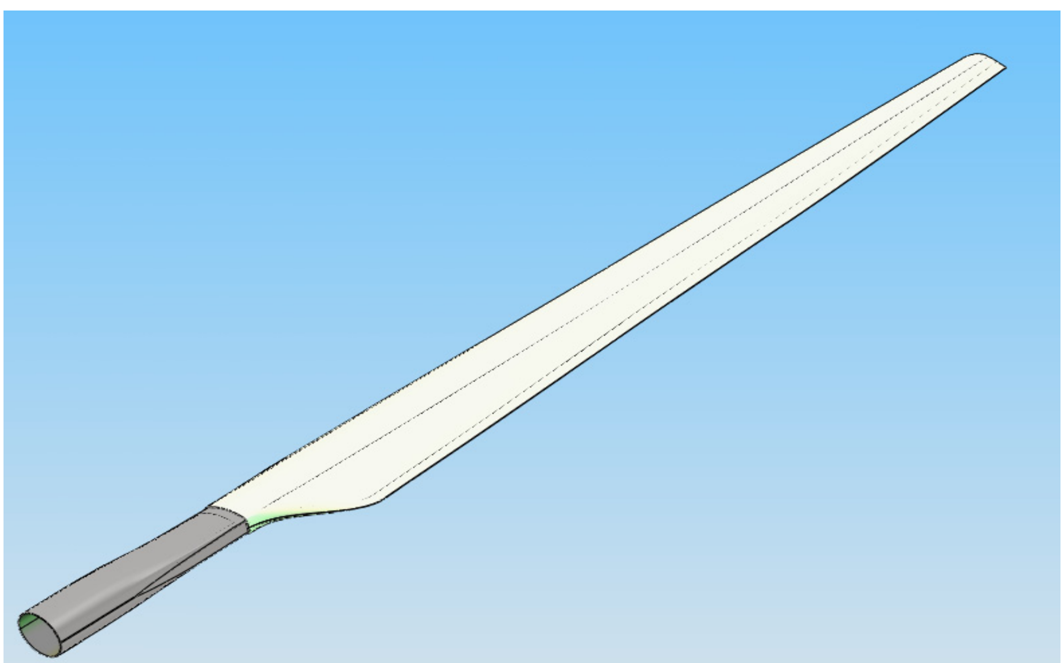


FIGURE 1, BLADE VISUALIZATION

We will describe the disadvantages of manual alternatives to this process and some of the special advantages of the automated process.

We will also outline the process and document some areas where further improvement to the process is needed.

SHORTCOMINGS OF MANUAL BLADE DRAFTING TECHNIQUES:

The overall geometry of a wind turbine blade is usually defined early in the design process by reliance on a combination of aerodynamic, structural and dynamic codes which define the general design parameters of the blade.

Typically, this process results in a specification which roughly defines the blade in terms of chord length, twist, airfoil section, and preliminary laminate schedule or other information defining structural properties. This information is provided for a number of spanwise stations along the blade, usually in tabular form. This data set often omits the tip planform profile, and provides sketchy information, if any, regarding the transition section of the blade where the airfoil shape of the outer portion of the blade is adapted to the hub attachment.

Many wind turbine blades are lofted from the above information using manual techniques. Even in cases where automated procedures are used to draft the geometry of the blade, these procedures tend to be based on highly task-specific codes which are costly to implement, and are limited in versatility and ease of design visualization.

All of these techniques result in drafting standards which have a real negative impact on both the efficiency of the design and analysis process and the quality of the physical blade which is built.

Critical aspects of the blade, such as tip geometry, structural load paths in the transition section, and geometry of internal structural features are left somewhat to chance, often relying on artistic intuition of the detail drafter—or even of the mold maker. Without slighting the contribution of these highly skilled personnel, it is important to note that there are many reasons why this freehand design can have a serious negative impact on the blade design.

ADVANTAGES OF AUTOMATED LOFTING

Before providing an overview of the process, it is well to document some of the advantages of the process relative to older manual techniques.

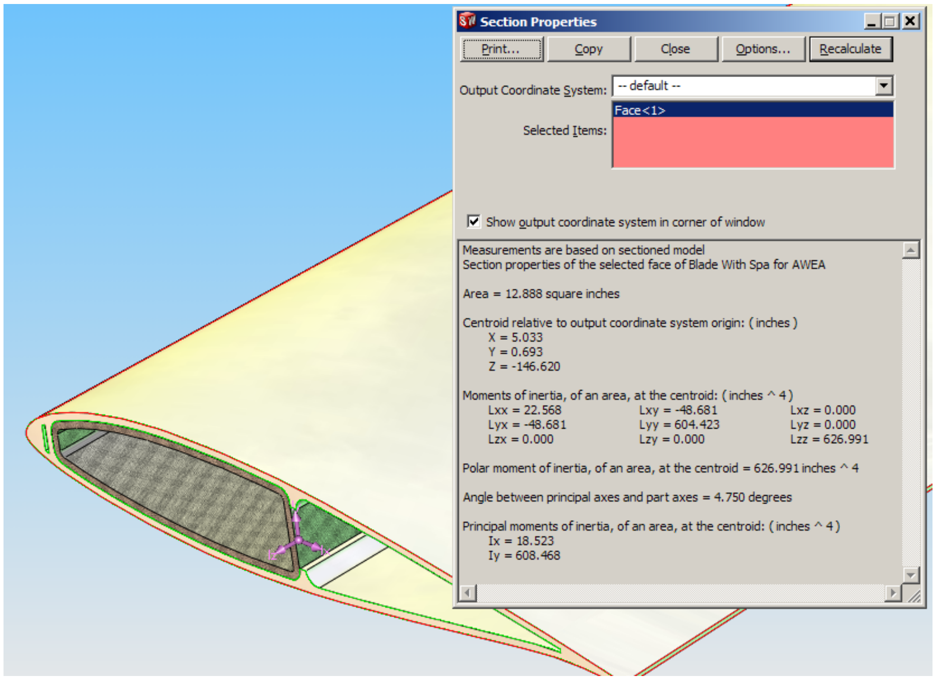


FIGURE 2, SECTION VIEW, SECTION PROPERTIES

Commercial solids modeling packages provide excellent visualization capabilities: The blade is rendered in as a three-dimensional solid image which can be rotated at will for examination at any angle. Internal features can be easily examined using section displays, providing information which might otherwise only be available by tedious manual drafting or by physically cutting up a finished part. Complete section properties for any chosen section are available with little effort. Powerful advanced display capabilities, such as elaborate virtual lighting, surface curvature plotting, and zebra-stripe displays can provide valuable insight into to the geometry which might otherwise only be available after a part was built. These display capabilities are available even in relatively modestly priced solids modeling packages such as SolidWorks.

The geometry definition is mathematically complete: No aspects of the design are left to a mold-maker's skill in fairing. Complete geometry definition within the software environment allows design iteration at a detailed level without wasted physical construction. Although the geometry of turbine blades is often quite straight-forward over large portions of the span, there are areas, such as the transition from the airfoil section to the hub attachment point where the geometry has some complexity. For example, the load path from the end of the D spar web into the circular inboard spar is a critical area which is often inadequately specified.

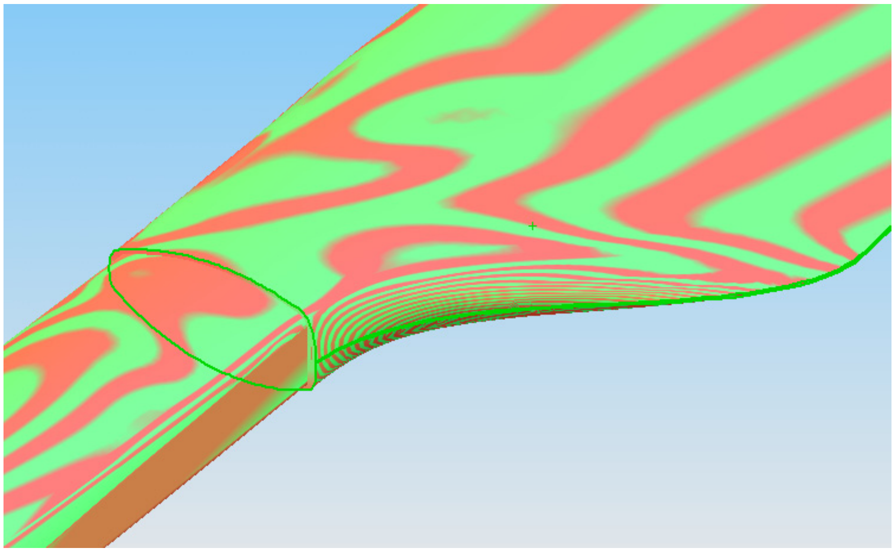


FIGURE 3, FULLY DEFINED TRANSITION SECTION, ZEBRA STRIPING

Design iteration is comparatively painless: Manual lofting, or lofting assisted using blade-specific codes, is tedious and expensive. Early stages of the design process can be completed using PROP and similar aerodynamic prediction codes, as well as other codes which predict structural, dynamic, and aeroelastic properties of the blade. Many of these codes run quickly and easily. At this stage, iteration is fairly painless, but the ability to visualize the finished blade is quite poor. Once manual lofting begins, visualization is better, but design iteration becomes a rather painful process.

If an issue appears late in the design process, the potential cost and tedious effort involved in redesign can cloud the judgment of the designer and reviewing management. Indeed, in any design process there comes a point where the potential improvement in the finished product truly does not justify the cost of additional design iteration. Any method which reduces the cost of carrying out a design iteration allows for a real improvement in the quality of the finished product.

Using our process, a blade can be re-lofted to the point where the outer surface is fully defined in a matter of minutes. Allowing for time to review the geometry, and to select changes for the next iteration, as many as two or three design iterations to this stage can be completed within an hour. Design iteration loops which return back to aerodynamic prediction codes from stages where the blade shape has been available for visualization are entirely reasonable.

Carrying the lofting to a later stage, where both the external and internal geometries of the blade are pretty well blocked out, can be accomplished in less than a day. Allowing for analysis, evaluation, and redesign, several iterations to this stage can be completed within a week. Use of Finite Element Modeling packages and other analytic tools is easily integrated with the design process.

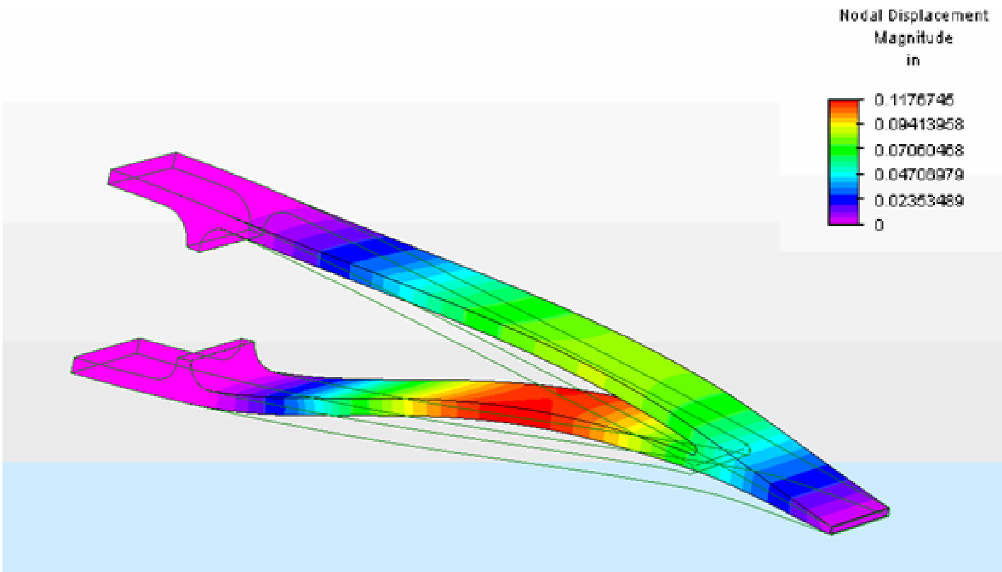


FIGURE 4, FINITE ELEMENT MODELING SUPPORT

Future improvements to the process should allow for even more dramatic reduction in the time and effort involved in carrying out design iterations.

Design variation is also comparatively painless: As is the case with iteration in a specific design case, the process facilitates design variation to create a family of similar blades. A family of blades might share common structural and manufacturing details, but be varied in overall planform to serve as replacement blades for a variety of turbines. Alternatively, subtle planform variations could provide different blades for a single machine optimized for differing wind conditions.

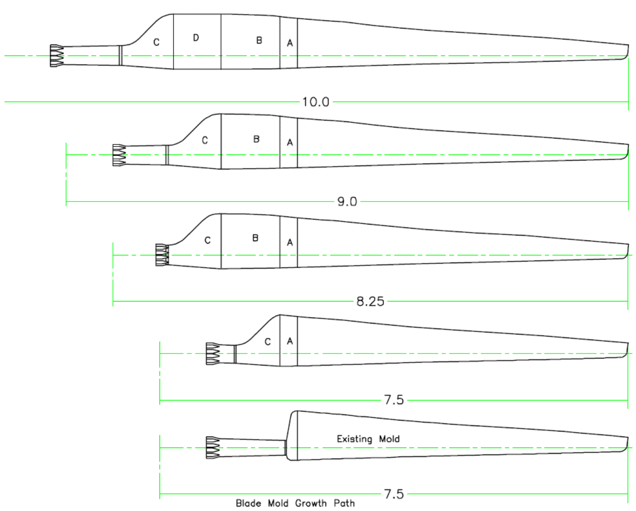


FIGURE 5, DESIGN VARIATION

The author's client plans to carry this variation flexibility a further step, to the point where a family of similar blades can be built from a single mold set, by assembling different combinations of mold sections to make blades for different applications. Although there are obvious shortcomings to this approach, it may provide an economically viable means of marketing a number of different limited-production blade designs for a variety of replacement and prototype markets where the anticipated production volume for any one application would not justify the cost of the mold. Without the benefits of automated lofting, such an approach would be very difficult to accomplish.

OVERVIEW OF AUTOMATED LOFTING TECHNIQUE:

The lofting process is carried out in a number of steps. For the project described, the blade consists of a high density Reaction Injection Molded (RIM) polyurethane skin supported by a braided carbon fiber/epoxy spar.

We will describe the process as it was developed for this structural system. It should be apparent that variations in the lofting process would be required to adapt it to a conventional fiberglass design or to other manufacturing techniques.

In overview, an Excel spreadsheet is prepared tabulating both the external and the internal geometric properties of the blade at each station. No math capabilities of Excel are used. The file is simply a convenient means of tabulating the input information which is easily displayed and printed for the user, and also easily read by a Visual Basic macro program (VB Macro) within the solid modeling package. The spreadsheet references section geometry files for each of the airfoils or other sections used in the design.

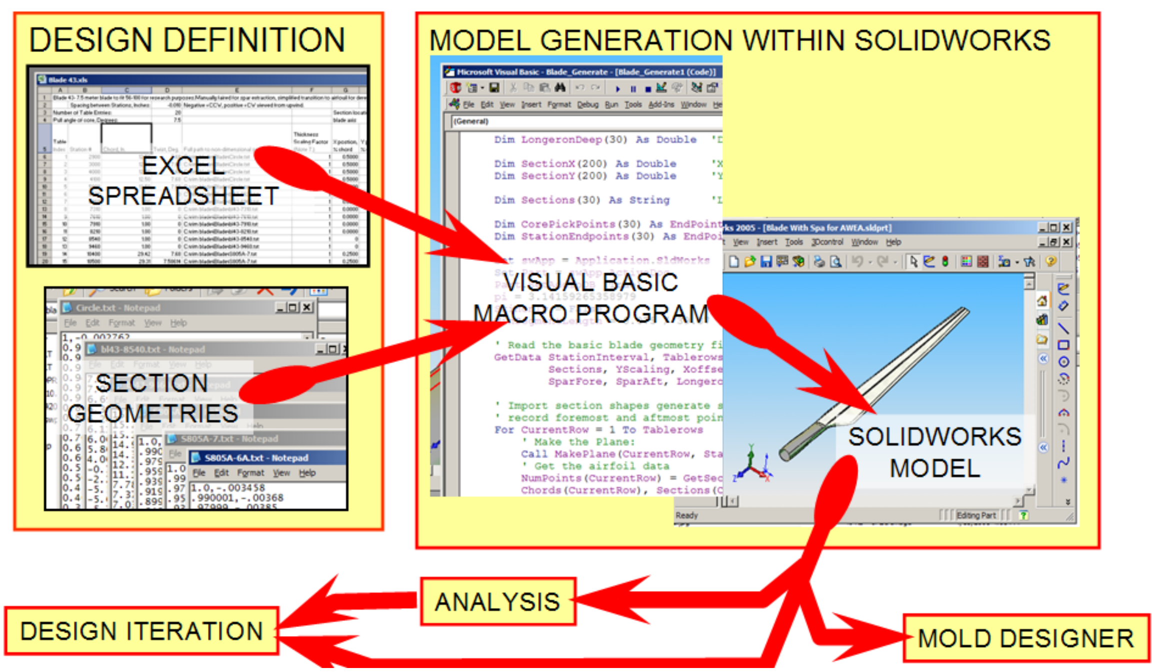


FIGURE 6, OVERVIEW OF LOFTING TECHNIQUE

Within SolidWorks, the VB Macro reads the spreadsheet and generates a matching solid model of the blade geometry. The macro proceeds largely automatically in a number of steps as outlined below.

If the resulting blade does not meet structural, aesthetic or manufacturability requirements, design iteration is possible simply by changing the necessary spreadsheet table entries and repeating the automated modeling process. Ultimately, the solid model provides a completely defined geometry input to the manufacturing process. In the case of the current project, the blade geometry is imported into a computer assisted machining program (MasterCam) which controls the mills that machine the molds.

External Geometry: The initial stage of the process consists of developing the external geometry of the blade. As with manual lofting techniques, a number of stations are defined. Each station has a number of properties, including:

- Distance of the station from some spanwise reference point (often the axis of rotation).
- A cross-section shape for the station. This section shape is specified by reference to a file which defines the section geometry in terms of the x and y coordinates of a number of points on the section. In outboard portions of the blade, these section geometry files often describe established standard airfoil sections normalized to unit chord length. For inboard and transition sections circular or other (perhaps custom designed) sections are defined.
- A primary scaling factor. For the airfoil sections, tabulated in unit chord terms, this factor is the desired chord length itself.
- A thickness scaling factor. For the airfoil sections, this factor is unity, resulting in airfoils of normal thickness proportions. This factor can be adjusted to give thicker-than-usual airfoils for the transition, and can, for example, be applied to a circular cross section shape to generate a family of ellipses of different aspect ratios as the blade shape fairs into a circular blade root.
- An X offset factor as a fraction of chord to locate the section in the chordwise direction relative to the reference centerline of the blade. Often the reference centerline will be the pitch axis of the blade, and the X offset factor will be 0.25 to place the pitch axis of the blade at the quarter chord.
- A similar Y offset factor as a fraction of chord to locate the section in the flapwise direction. Often this setting will be 0, although variations may be necessary in the transition section to achieve a suitable transition from the airfoils, which are asymmetric in the flapwise direction, to circular and elliptical transition sections which are often symmetrical in both the x and y direction about the pitch axis.
- A twist value, defining the angle between the chord line and the plane of rotation of the rotor.

Rather straightforward analytic geometry is applied to the section data to get cross sections for each station scaled, twisted, and located appropriately for the blade. The built-in lofting capabilities of the solids modeling package are then called on to fair the surface of the blade.

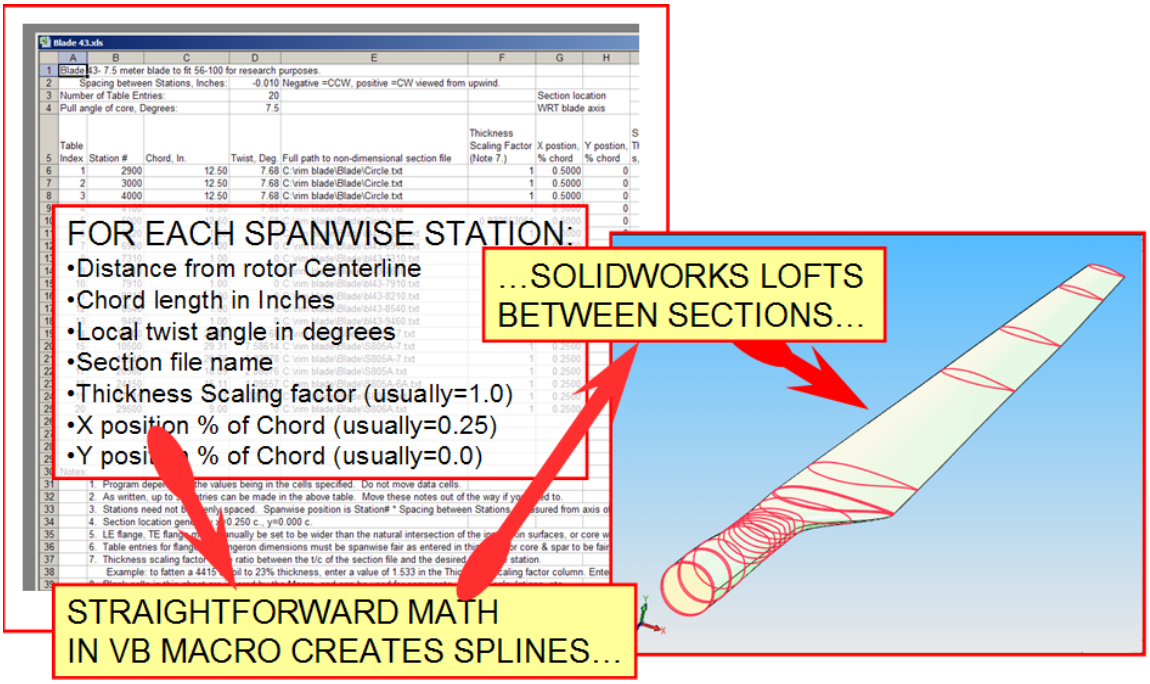


FIGURE 7, LOFTING EXTERNAL GEOMETRY

Internal Geometry Overview: The internal geometry is specific to the structure of the RIM polyurethane skin/braided carbon fiber spar for which the lofting process was developed. The upper and lower polyurethane skins are each separately molded in matched two part aluminum molds. A mathematically complete internal geometry is necessary in order to machine the molds. In order to accurately locate the skins on the structural spar and to provide consistent geometric, elastic, and mass properties to the blade, the geometric definition must not only be complete, but also accurate.

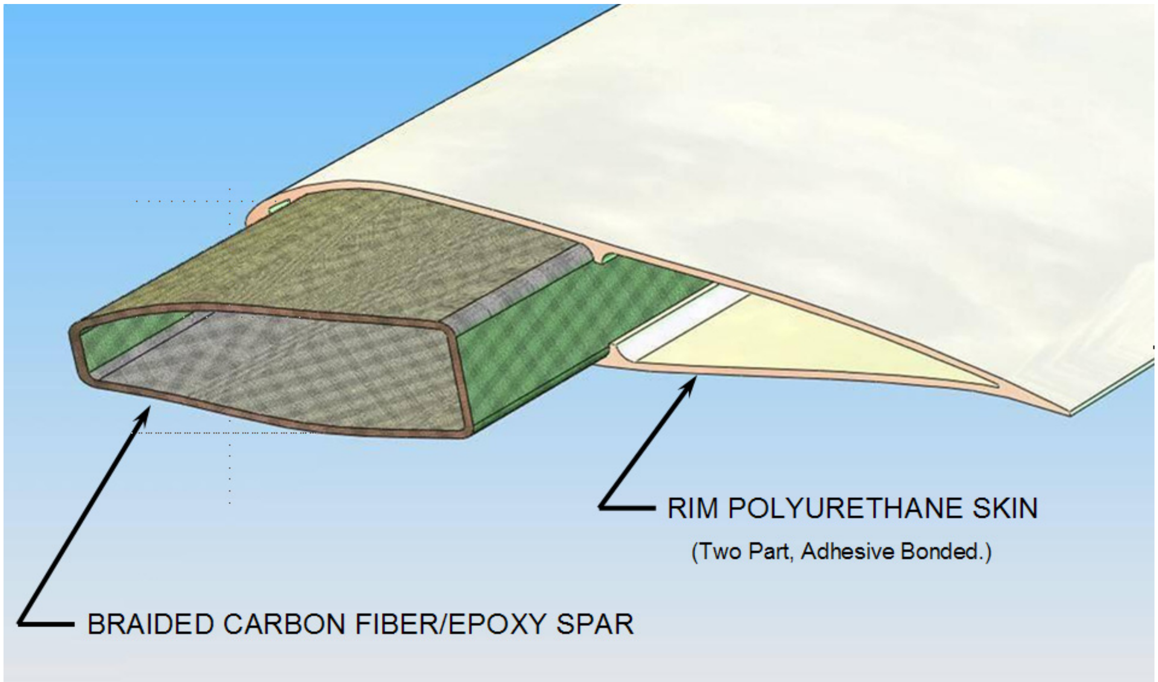


FIGURE 8, INTERNAL STRUCTURE OF CURRENT PROJECT

Internal skin features include the thickness of the skin from the outer surface, the geometry of the joints between the skin halves, and the location and section characteristics of longitudinal ribs which serve a number of functions, including stiffening, locating the skin on the spar, and providing for material flow in the molding process.

The internal geometry generated by the current work is directly applicable only to the RIM skin/braided spar structural system. It is important to emphasize that modifications to the VB Macro to support other manufacturing methods would be straightforward.

Inner Surface of the Skin: SolidWorks provides an automated shelling feature, which allows any solid volume to be shelled out into a hollow shape. This shelling feature works properly for shapes formed by lofting spline sections which do not include sharp corners. The feature also works properly for shapes formed from primitive geometric shapes, even if they do include sharp corners. SolidWorks' automated shelling does not work for lofted splines which have sharp corners—In other words, it does not work for windmill blades. Additionally, the automated shelling does not provide for tapered skin thickness, which is usually desired in a blade.

In order to shell the blade, we developed a process to offset the sections for the outer surface the desired thickness inwards. Using simple analytic geometry within the VB Macro, perpendiculars to the outer skin surface of a length equal to the desired thickness are erected at each tabulated point. Each of these perpendicular points is checked and those that are too close to any other portion of the blade external surface are eliminated. The remaining points form a spline which defines the inner surface of the skin.

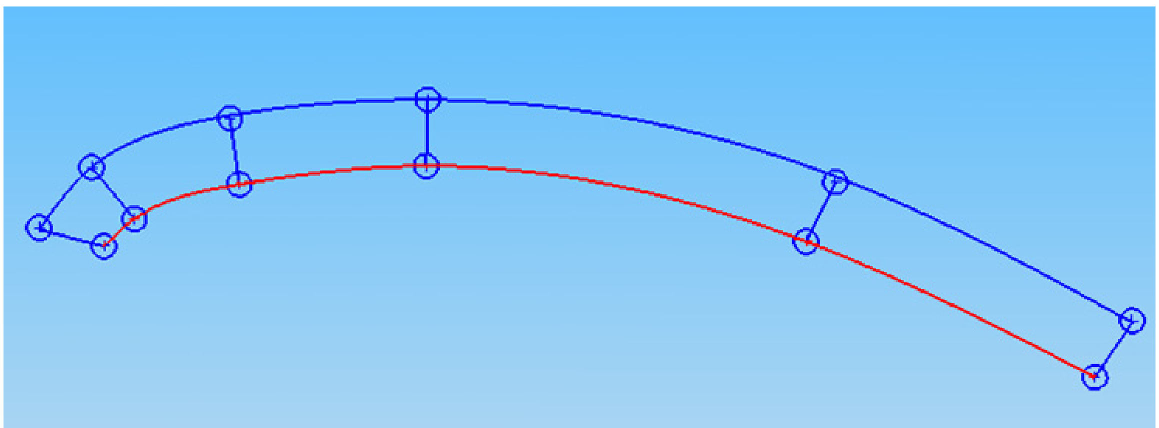


FIGURE 9, GENERATING INTERNAL SURFACE PROFILE (RED) FROM OUTER SURFACE (BLUE). (SIMPLIFIED ILLUSTRATION.)

This inner surface is lofted as a solid, and using Boolean solids combination capabilities of SolidWorks, subtracted from the solid defined by the outer surface blade shape to form the skin.

It is important to emphasize that the skin model is not simply a three dimensional surface, but is in fact a three dimensional solid with separate inner and outer surfaces. This distinction is critical both for export of the model the CAM software which allows for machining of the molds and for export to FEM packages for accurate solid-element structural modeling.

Internal Skin Details: The skin is not a simple hollow shell, but has longitudinal ribs to locate it on the spar, and added flange material at the leading and trailing edges of the skin forming flanges where the skin halves are bonded to each other. As an example, we will provide a rough overview of the generation of the trailing edge flange. Generation of the longitudinal ribs and the leading edge flange proceed in a similar manner.

As a first step, the aftmost point on the outer surface of the blade at each station is found. These points are formed into a spanwise spline defining the trailing edge of the blade. An additional set of points, chosen by offsetting the trailing edge forward by the desired flange width, are formed into another spanwise spline which defines the forward inner surface of the flange. These splines are joined at the inboard and tip end, forming a closed contour section which is extruded into a solid extending well above and below the outer surface of the blade. This solid is combined using a Boolean AND operation with a copy of the original solid blade and the resulting part is combined using the Boolean OR operation with the skin simple skin to form the flanged skin.

Spar Generation: The spar is generated by forming a solid defined by the cavity within the skin, trimming off the portions extending forward and aft of the longitudinal ribs, and then shelling the result.

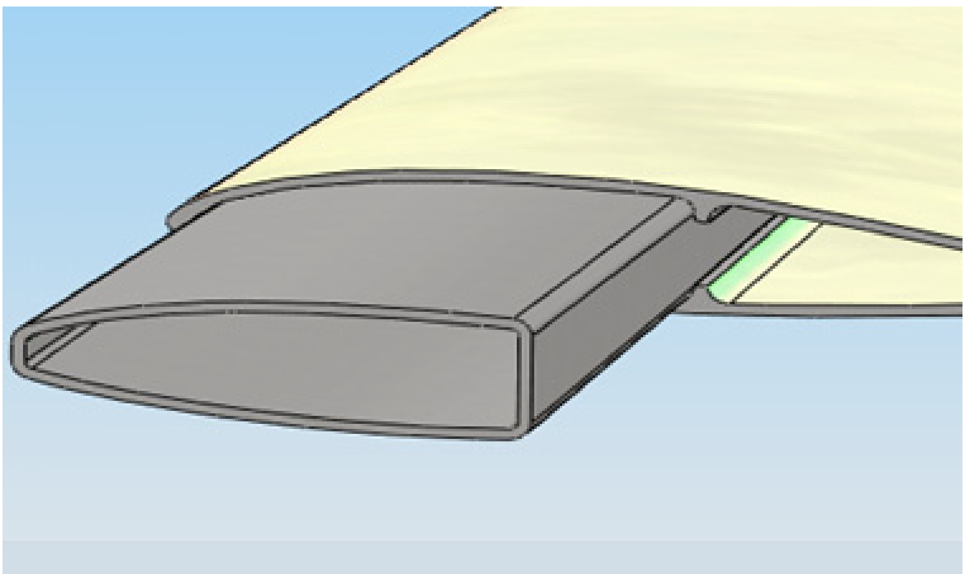


FIGURE 10, SPAR GENERATED FROM INTERNAL SURFACE OF SKIN

MANUAL STEPS, PROCESS SHORTCOMINGS, AND FUTURE WORK:

The method is currently in an early stage of development. A number of manual steps are necessary to complete the blade. There are also steps where the VB Macro does not operate reliably, and manual intervention in the automatic process is occasionally needed. There are also a number of limitations in the geometric definition, which we plan to address in future work.

We suspect that some of the more costly solids modeling packages (Pro-E, Wildfire, etc.) might, in some cases, operate more reliably and automatically than SolidWorks, which is a fairly inexpensive package. In fairness to SolidWorks—and in the process emphasizing the benefit of its low cost—we should point out that we do not yet have the resources to buy and get trained in any of the more expensive packages to confirm this suspicion.

Lofting failures: There are a number of ways in which the lofting process to form a solid volume, such as the skin outer surface, can fail. One common failure, for example, is colloquially called “Bowties”. Rather than lofting in the desired manner, for example with lines connecting from the trailing edge on one section to the corresponding point on the trailing edge of the next station outboard, the lofting process might connect the trailing edge of one station with the leading edge of the next. This results in a useless geometry which looks rather like a bowtie.

In manual operation, SolidWorks provides a means for selecting the points to for guide curves to insure that this does not happen. Annoyingly, we have not been able to duplicate this capability in under macro control. Often the program will make the correct assumptions and loft the surface properly, occasionally it will not. For the present work, we run the macro in a debug mode which allows us to insert breakpoints after each loft process. If a loft fails to complete automatically, we can complete it manually and then resume automatic operation at the next program step following the breakpoint.

Even with the annoyance of “babysitting” the lofting process and helping the program through these rough spots, automated lofting remains an extreme improvement over manually drafting the blade, either on paper or in a solids modeling package.

Two Dimensional Approximations: A number of operations, including generation of the flanges and the skin thickness itself are currently based on two-dimensional approximations which neglect curvature in the spanwise direction. In the outer portions of the blade, spanwise variation is shape is very gradual and the error introduced is truly negligible. In the inner portion of the blade, particularly if there is a somewhat abrupt transition from airfoil shape to the shape that attaches to the hub, the error can become significant.

At present, manual adjustments of spreadsheet values for skin thickness and flange widths can approximately compensate for the error. In the future we plan to generalize the thickness calculation to more accurately consider spanwise curvature. The programming to accomplish this will be tedious, but relatively straightforward.

Limitations in Accuracy of Shelling at Leading and Trailing Edges: The method used to generate the inner surface of the skin using only the tabulated airfoil data points, results in significant errors near the leading and trailing edges of the sections. In the current design these points are masked by the flange material, and thus do not affect the finished geometry of the part.

In future work, or in other structural designs, where these flanges might be thinner than the spacing between tabulated airfoil sections or omitted entirely, the errors in generating the inner surface of the skin might be problematic. Again, tedious, but straightforward programming can correct this.

Constant Chordwise Skin and Spar Thickness: As currently developed, the method only handles constant skin thickness chordwise at any particular spanwise station. For our client’s initial molding trials skin thickness has been held constant both spanwise and chordwise, so this limitation has not been an issue. As the RIM skin/braided spar process matures into a production technology, and certainly for other applications, chordwise variation in skin thickness and spar thickness are very likely to be needed. Adding this capability when it is needed will be straightforward.

Formation of Parting Line between Skin Halves: At present the parting line between the skin halves is generated manually. This area includes a variety of details which are time-consuming to draft, Including "zipper teeth" to make the skins self-fixturing in alignment, relief to allow for glue lines, and the like.

In the long run, this tedious manual work should be replaced by macro commands. At the time the VB Macro was developed the architecture of this joint had not yet been defined. This was also a detail which did not reflect back heavily on earlier steps in the design process. Once the concept of the joint was defined, the details did not need to be part of the iterative design process, but only had to be carried out once. For future work, particularly if a family of similar blades were to be developed; automating this process would be very desirable.

Formation of Fillets and Radii: At present formation of fillets and radii—for example, the radii between the skin inner surfaces and the longitudinal ribs—are carried out manually. We have not yet been able to create the necessary variable radius fillets under macro control. (Indeed, reliably generating the fillets between multiple lofted surfaces *manually* seems failure-prone too.)

We would very much like to add this to the automated process. While manually specifying a fillet does not take long, once specified it can take SolidWorks a very long time to attempt to actually form the fillet—especially between lofted surfaces. It seems preferable to form fillets one at the time. As a result, the user spends a great deal of time waiting for one fillet to form so the command can be issued to start the next.

Formation of Tip Geometry and Root Attachment Details: At present the macro program does not automatically form the tip geometry or the details of the interface between the spar and hub attachment hardware.

At present, generation of these details is not tedious enough to justify their inclusion in the automated macro. Note that to the extent multiple sections are accurately defined for the tip, the tip can be automatically generated. It is only the detailed radiusing and planform definition beyond what can be specified by conventional sections which is not automatically generated.

We do not see this as a major issue at this point. It is important to note that these details can—and must—be manually completed within the solid modeling package and become part of the mathematically complete definition of the blade. Manual completion of such details it not tremendously tedious, and to gain full benefit from the method, it is essential that all the details of the blade be fully defined.

SUMMARY:

Automated lofting using SolidWorks, a comparatively inexpensive solids modeling package has been demonstrated. The technique has been a valuable time-saver in the context of the 7.5 meter to 10 meter RIM polyurethane skin/braided carbon fiber spar blade family being developed for Composite Engineering Inc. and its associates.

This experience shows that the technique, or variations on it, is potentially valuable for other design activities, blades in other size categories, blades of other geometries, and even design of other articles, including aircraft lifting and control surfaces, sailboat keels and rudders, and perhaps even complete vessel hull or airframe designs.

Some shortcomings of the process appear to be related to limitations of the SolidWorks solid modeling package. It is not clear the extent to which these limitations might be avoided by transitioning to a more expensive package such as Pro-E or Wildfire. Given a larger budget, or for an organization already equipped with, and trained in the use of, the more expensive packages this would certainly be worth exploring. The Macro programming approach should be adaptable to any of these packages.

Other shortcomings of the process simply result from the early stage of our development of the technique, and can easily be corrected with further work.

Even despite these shortcomings, the technique is a dramatic improvement over techniques such as manual lofting or lofting using task-specific computer programs.

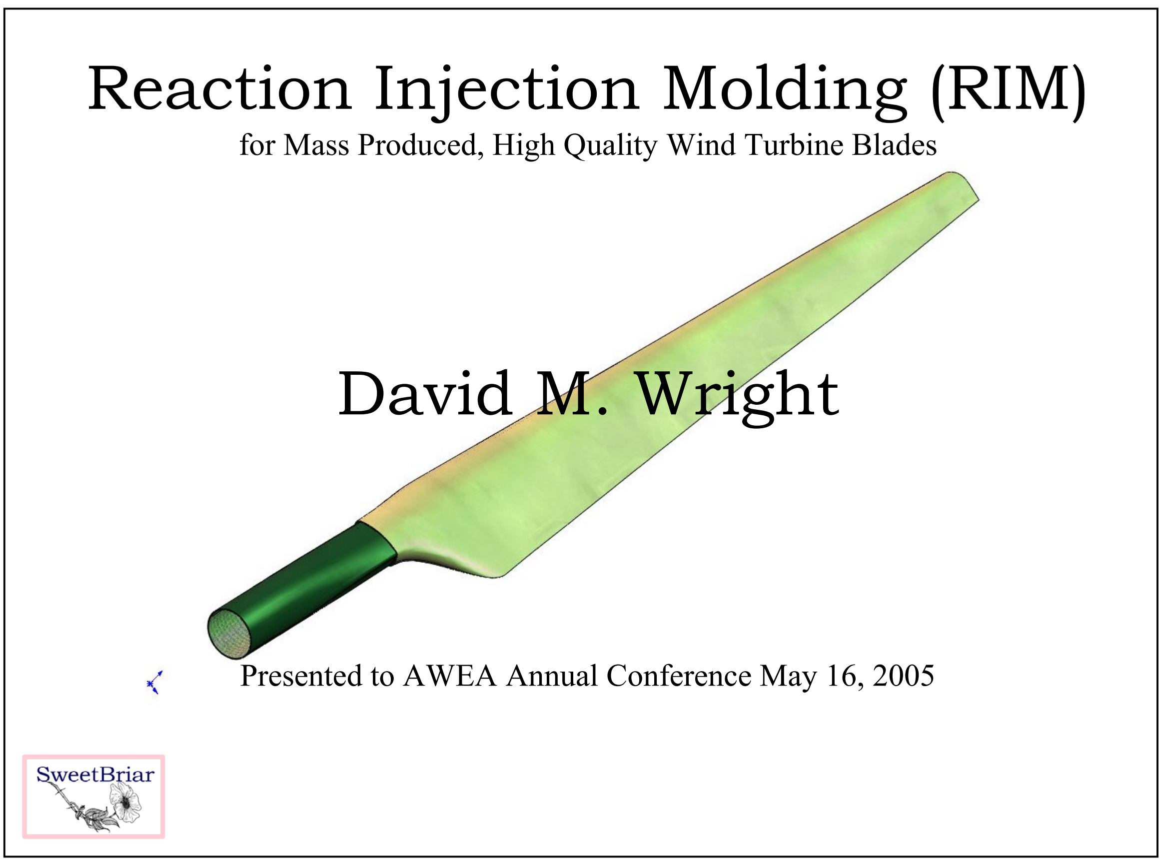
Appendix B

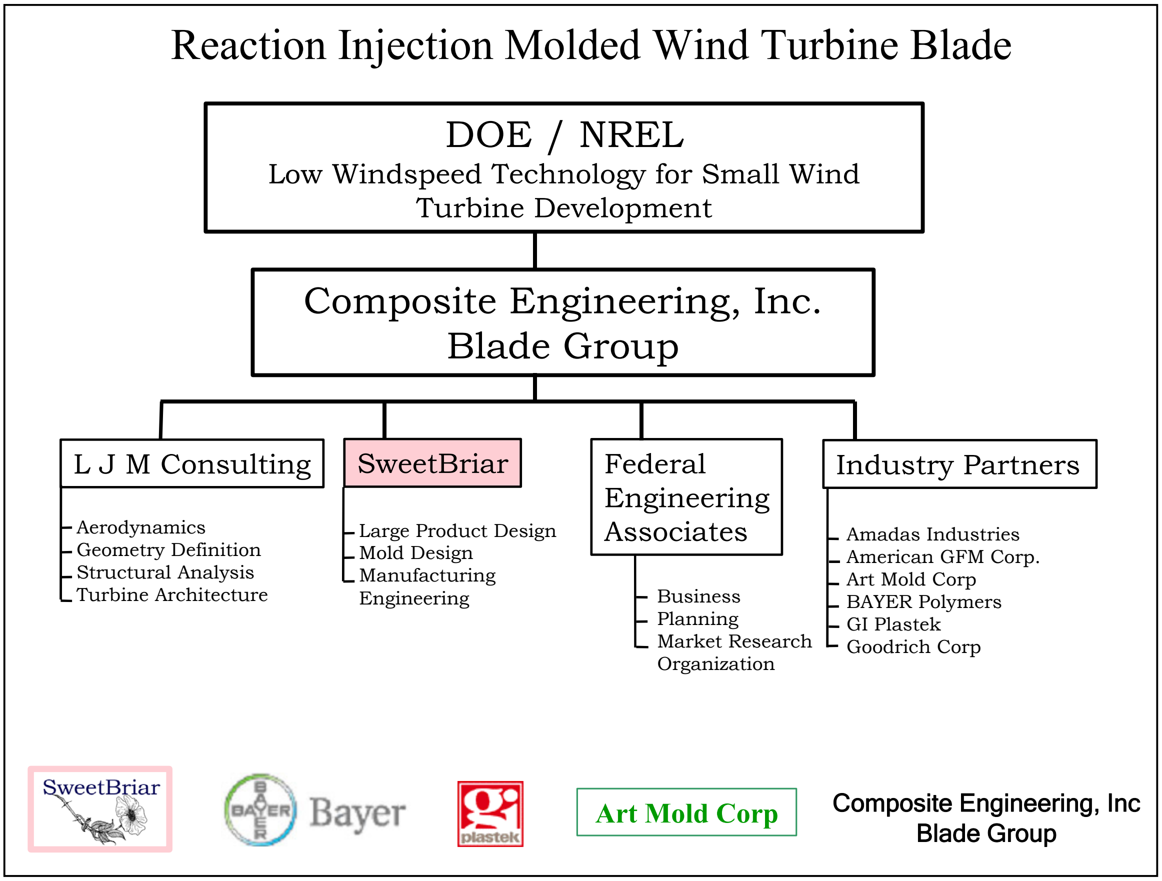
Acknowledgment: "This material is based upon work supported by the Department of Energy under Grant Number DE-FG36-04GO14256."

RIM, Reaction Injection Molding, A High Quality Wind Turbine Blade

David M. Wright
May 25, 2005

Presented May 16, 2005 at the AWEA 2005 Conference in Denver CO




Reaction Injection Molded Wind Turbine Blade
DOE / NREL
Low Windspeed Technology for Small Wind Turbine Development
Composite Engineering, Inc.
Blade Group
L J M Consulting
Aerodynamics
Geometry Definition
Structural Analysis
Turbine Architecture
SweetBriar
Large Product Design
Mold Design
Manufacturing Engineering
Federal Engineering Associates
Business Planning
Market Research
Organization
Industry Partners
Amadas Industries
American GFM Corp.
Art Mold Corp
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Goodrich Corp
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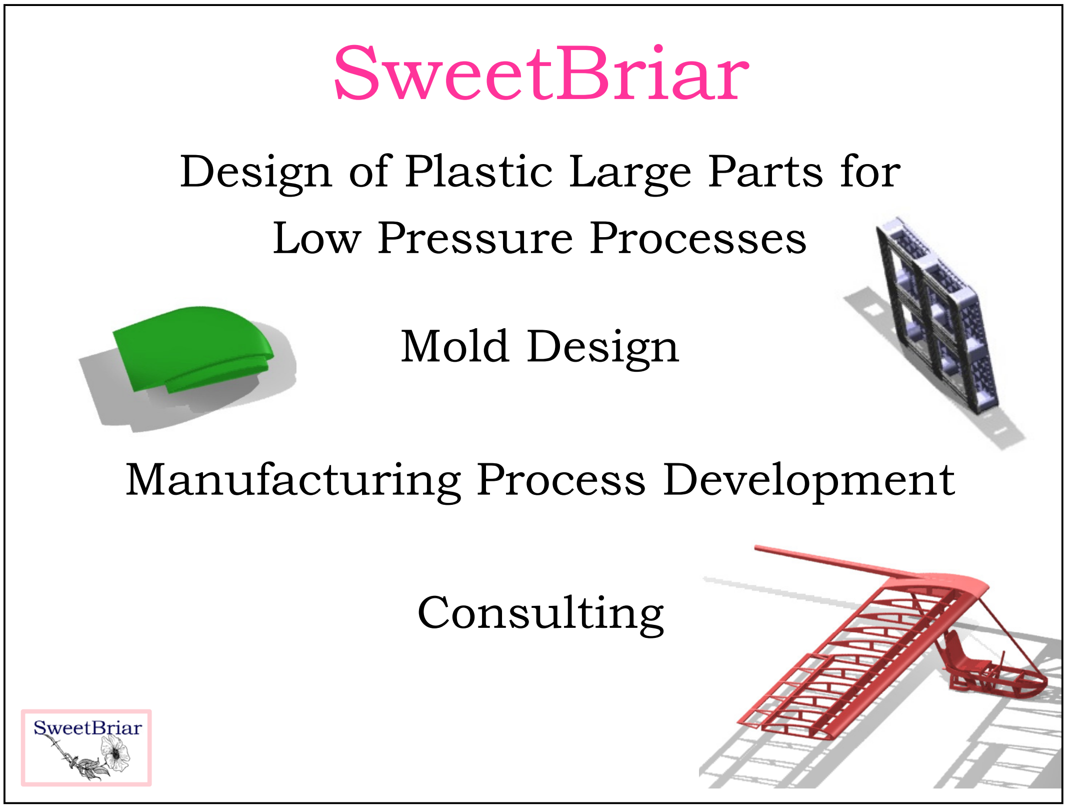


SweetBriar

SweetBriar is a consultancy specializing in developing large plastic articles, providing technical support to the wind industry and a technical editing service. This year we assisted in the preparation of 3 proposals for the latest round of LSWT RFPs. We have designed large plastic parts for several industries including medical, recreational and industrial and the systems to produce them. Some examples are shown above. From left to right:

A blade tip for Portland Wind Electric's new 42kW wind turbine. The 3D model was used to prepare SLA models in ABS that will be used as tips for the prototype blades.

A two-piece rackable pallet for a proposal to PEPSICO by a group of minority investors as part of a recycling project. The structural foam parts are molded in high-density polyethylene (HDPE) and sonically welded together.

The ongoing design of what my wife describes as Dave's Gyro Gearloose Project, an ultra-light glider based on a primary glider used to train German glider pilots between the wars. This design features a cantilevered wing with a carbon-epoxy spar, rather than the original strut and wire design.

Our editing service prepared a book for publication and managed its production.

Blade Concept

Load Carrying Spar

Carbon / Epoxy

Compliant Skins

Polyurethane

Family of Sizes

7.5m 8.25m 9.0m 10.0m

Blade Concept

The choice of a molding method has been crucial to this project from its inception. The goal is to develop a manufacturing method that will produce an aerodynamically superior wind turbine blade that is light in weight, low in cost and extremely consistent. During the preparation of the proposal and later during the initial phase of the project we spent considerable time evaluating the various commercial manufacturing methods available. RIM skins and a carbon/epoxy spar were chosen as the most practical method of meeting the design objectives within the time and cost budget available.

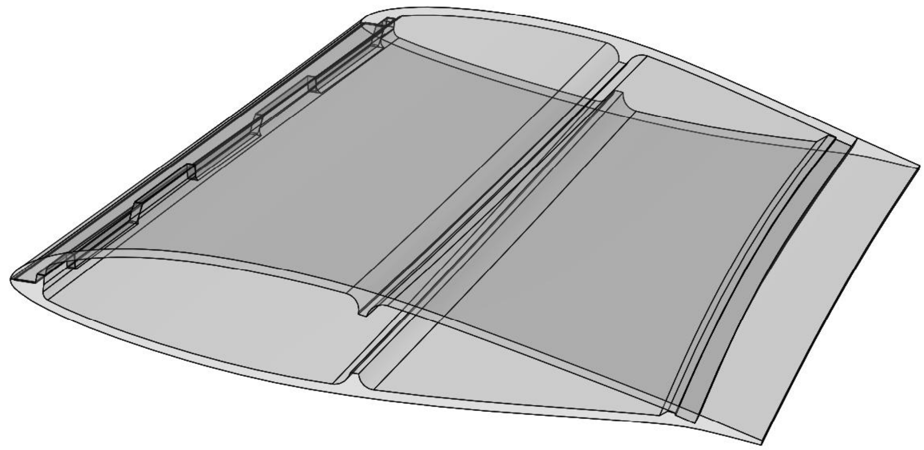
Spar

Strength 400ksi

Modulus 13 million

The spar is made from carbon tows braided into a triaxial fabric "sock" with the carbon fibers in the 0˚ direction and glass in the 45˚ direction. The vast majority of the fibers are carbon, which provides the strength, while the glass aligns the carbon tows. The structure, a "D" spar transitioning to a circle at the root, will be built up on a mandrel and vacuum infused with epoxy resin and cured in an auto-clave. The spar is lightweight, very strong and rigid and is designed to carry the bulk of the loads.

The root hub attachment will be incorporated into the braid prior to the infusion thus the entire load carrying structure will have only primary bonds, eliminating the problems associated with secondary bonds.

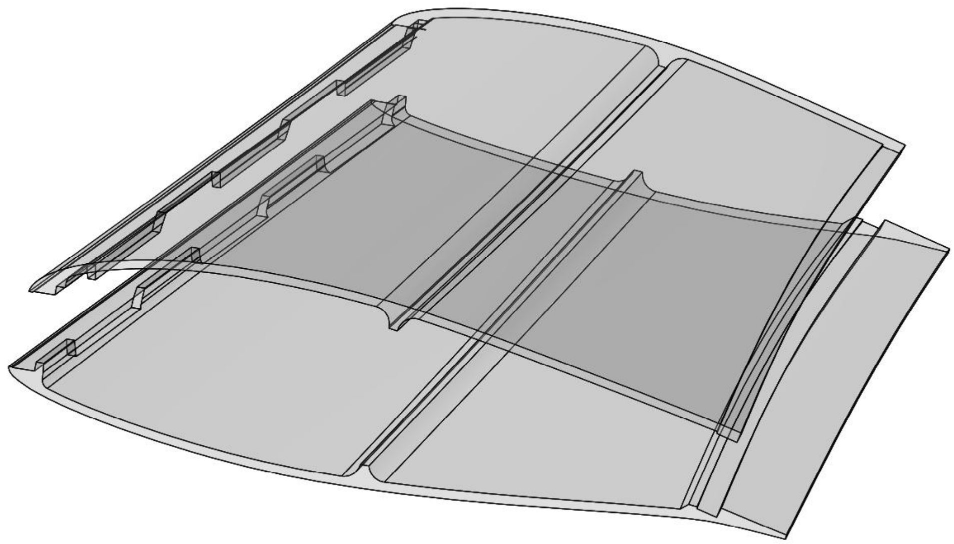


Half Transparent View of Trial Section

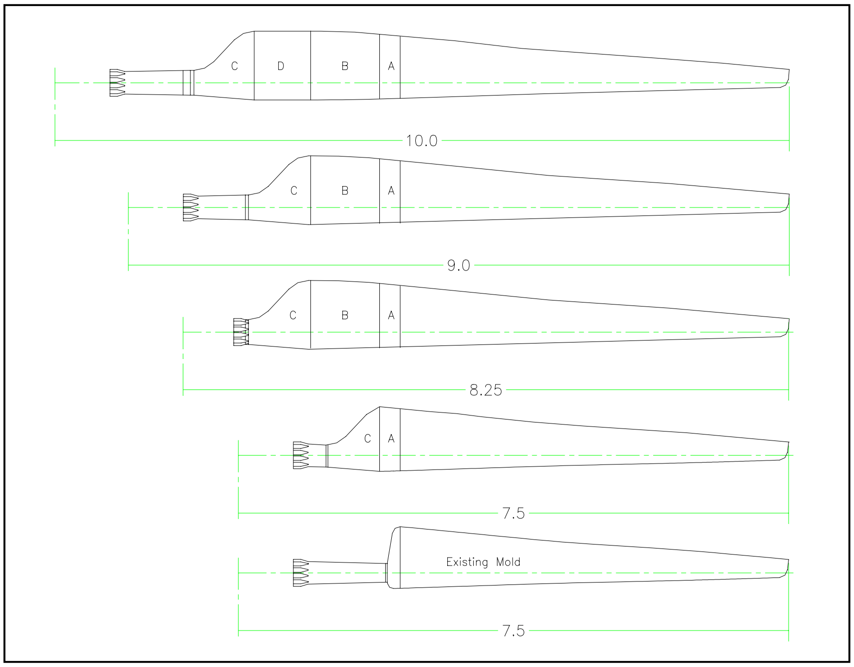
- **A flexible skin.**

The upper (suction) and lower (pressure) blade surfaces will be molded from a common grade of polyurethane and are the subject of this paper. Later in the paper I will describe the design and construction of the molds and the RIM process.

The molds used are "matched die sets", that is to say each mold consists of a core and cavity such that the entire part is contained within the mold. All surfaces of the skin are defined by the CNC machined mold. The resulting moldings are accurate, finely detailed and extremely consistent. This control of the entire geometry allows us to design in interlocking features to ease and simplify the assembly of the final blade. Elaborate fixtures will not required.

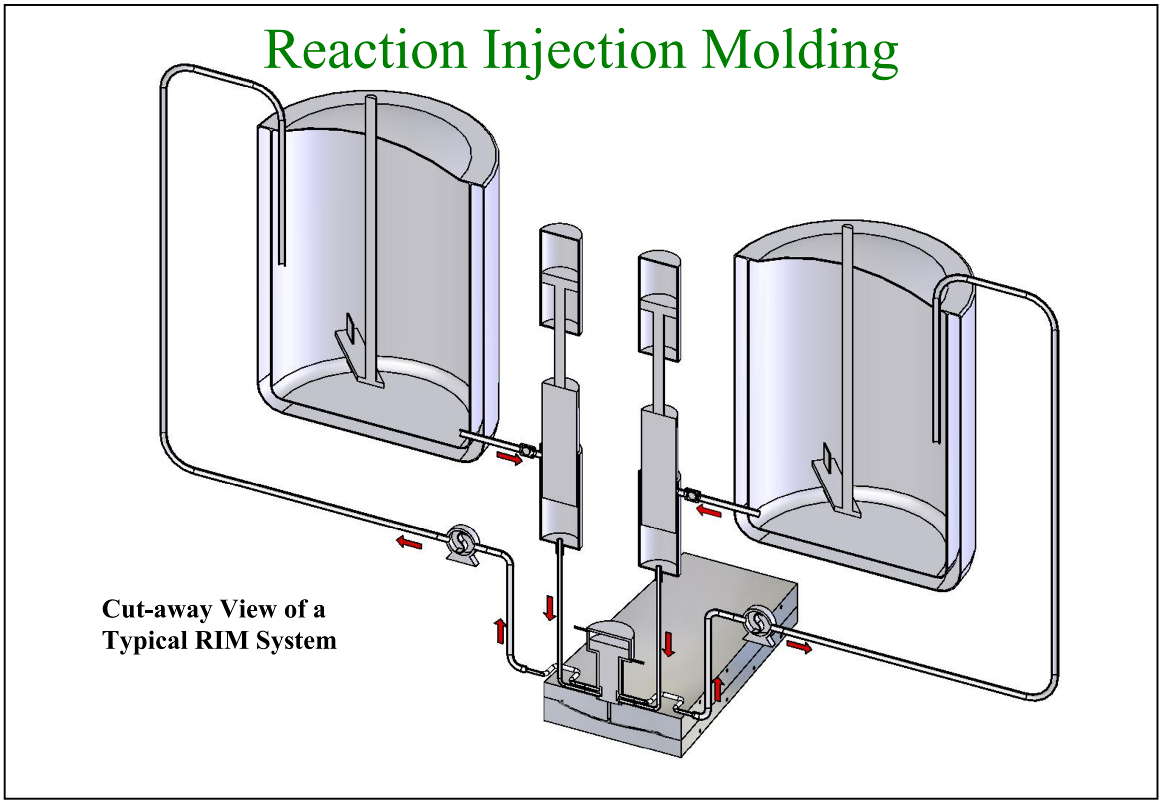


Exploded Cut-away View of Trial Section



- **A range of sizes.**

The molds are modular so that by adding or removing sections we will be able to offer the blades in a range of sizes. The tip section has been optimized in terms of chord and twist for a 9.0m blade. The inner sections will have constant chord but the twist will continue. The transition from full chord airfoil to spar section will be common to all but the smallest blade shown above.



So, what is RIM?

- **What it's not**

The process we are discussing today is not Resin Transfer Molding RTM, which in Europe is referred to as RIM. There is no fiber preform to be loaded into the mold prior to injecting the catalyzed resin into the mold.

- **What it is**

In simple terms in Reaction Injection Molding two or more reactive, low viscosity liquids are mixed at high velocity and high flow rates as they enter the mold. The mixture gels quickly, typically 4-6 seconds, and then over the next few minutes crosslinks (cures) until the part is strong enough to be safely removed from the mold. The crosslinking continues for a considerable time after ejection or demolding so support is often provided as the part cools.

- **Resin Systems**

RIM can be done using a number of different resin systems. By far the most common system used is based on urea and is known a polyurethane or simply urethane. I will cover the urethane system in more detail later.

All the systems are sensitive to water and DCPD is sensitive to oxygen so all must be processed in closed systems with provisions for shielding the reactants with dry air or an inert gas. Many are formulated with water scavengers such as micro-sieve.

- **Nylon**

Nylon 6, also used in cast systems, can be made by the anionic polymerization of ε-caprolactum, acyl lactum or a similar initiator, a metal catalyst and pre-made lactum chains at elevated temperatures (100-160˚C 212-320˚F). Nylons require conditioning systems that can accommodate the high temperatures used.

- **DCPD**

Dicyclopentadiene (DCPD) is a two-part system. When mixed, the reactants crosslink in a strongly exothermic reaction rapidly forming a gel first and then a nearly fully crosslinked solid with very little free monomer. Processing temperatures are low, (tanks at 35˚C-95˚F, molds at 50˚C-122˚F)

The polymer has good mechanical and chemical resistance properties and paints well, however it does not bond well and is not available in fiber filled formulations. (We later determined that DCPD parts bond very well once the surface has oxidized, and manufactured skins from DCPD.)

The lack of bonding properties prevented us from using this material. DCPD's higher modulus and strength as well as its better flow properties made it very attractive. Applications like nacelle panels, spinners and equipment covers that rely on mechanical fasteners may be well suited to DCPD. It is used in truck and automotive applications as exterior and hidden panels.

- **Polyurethane**

Polyurethanes are an incredibly versatile class of compounds that can be formulated to have properties suitable for products ranging from nearly spineless rubbery toy spiders and snakes, through low-density cushion padding, skinned automotive interior panels, to truck fenders and now wind turbine blades. The systems are formulated as thermoplastics for injection molding and thermosetting for casting and RIM. This paper will limit itself to the thermosetting formulations targeted for structural applications.

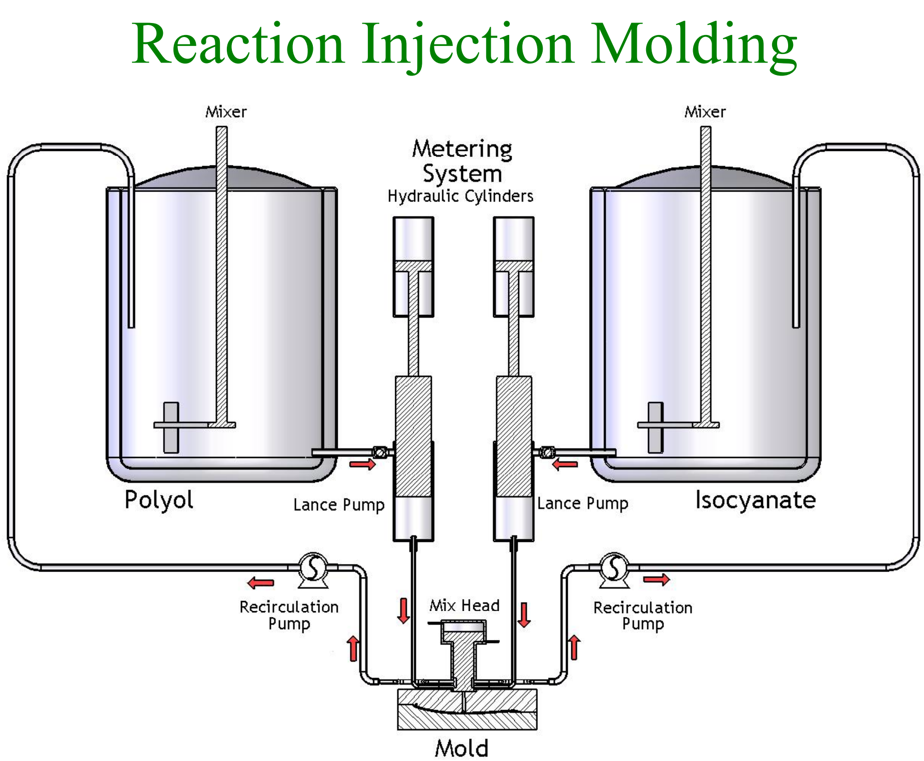
The resin systems used for RIM are blends of polyether and polyester polyols, isocyanates and processing aids. They may or may not have fillers and blowing agents. Common fillers are minerals that have some natural aspect ratio, like mica, wollastonite or round particles like talc or calcium carbonate, all of which are added to increase the modulus. Milled and flaked glass are used for modulus and strength improvement and small amounts of chopped glass can be used but doing so causes a drastic increase in the viscosity. The improvement in modulus by adding fillers is accompanied by a decrease in tensile and impact strength except in the case of chopped glass fibers.

Processing temperatures are a little higher than DCPD but well below nylon (tanks 55˚C-131˚F, molds 71˚C-160˚F.)

The major vendors, like our Industry Partner Bayer Material Science, are able and willing to modify their standard products to aid in processing and to achieve specific physical, chemical and electrical properties. The size of even small turbine blades is so large that even in industrially small numbers the quantities of resin are enough that vendors foresee a reasonably large sales potential. This sales potential encourages the suppliers to consider customization and application specific formulations.

- **The Process**
- **Bulk Tanks and air dryers**

Raw materials for the molding process are brought into the plant in containers ranging from pails to rail tank cars. Bulk deliveries are transferred to steel storage tanks, which may or may not be heated. All vents on the tanks are equipped with desiccators to protect the material from water. Materials are brought to the day tanks for metering to the molds. A metering system usually serves more than one molding station.



Schematic Diagram of a Metering system for RIM

Flow Diagram

- **Day tanks**

Day tanks are used to store and condition the raw materials. I show two tanks here as this arrangement is the most common, however a third and fourth tank are sometimes used to meter in special ingredients. These ingredients may not be used in all the products being fed by the system. The large tanks contain the primary reactants, a blend of polyols in one and the isocyanate in the other. The tanks are jacketed to allow temperature control and equipped with mixers to insure the blends are uniform and that any fillers are held in suspension. The vents have air dryers. Check valves are used to control the direction of flow.

- **Recirculation Pumps and heat exchangers**

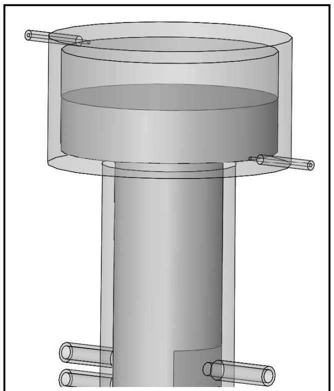
Each of the day tank systems is equipped with a recirculation pump and possibly a heat exchanger. The standard mix head has four ports so the smaller secondary tanks can be recirculated as well. The system is kept in slow recirculation until it is called on to deliver a charge to a molding machine. In preparation for a shot the lance pumps swing into action.

- **Lance Pumps**

The lance pumps are pistons loosely fitted into bores with a seal at the top. The pistons only contact the seals so that fillers, which are often abrasive, can be pumped with a minimum of wear on the metal parts. The pistons are connected to servo driven hydraulic cylinders, which are controlled by PLC. Polyurethane (PU) formulations for RIM are normally used in a one to one ratio, however the controllers can deliver other ratios because the pumps are provided with encoders that provide the system with feedback on the position of the lances. The controllers have multiple set points allowing several molds with different shot sizes to be serviced.

A shot delivery cycle begins with the system recirculating and the lances in the inward position. The lances are commanded to retract to a set point, the mix head shifts to the injection position and the lances are returned to their starting position. The mix head returns to the recirculating position, cleaning the mixing chamber and awaiting the next shot.

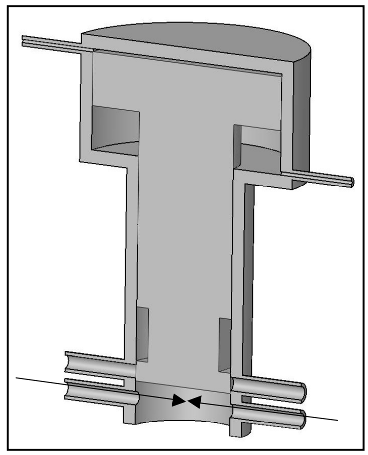
- **Mix Head**



Mix Head A

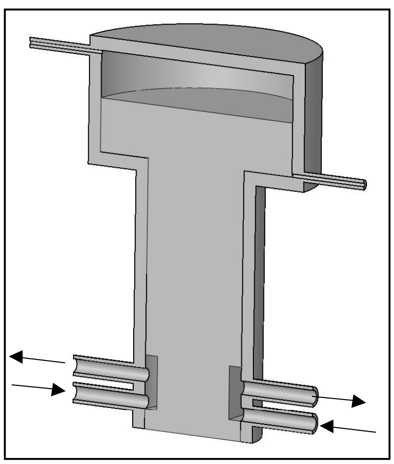
The mix head is a plunger in a fitted bore attached to a hydraulic cylinder. It is often manufactured as a single unit. The head mounts directly to the mold and feeds an after mixer, a runner and a gate. We have not used that arrangement because our part design provides a large span wise rib that will serve as a flow channel to help deliver the reacting polymer to the length of the blade.

The Mix Head A illustration shows a mixer simplified for clarity, with two ports, in the recirculation position. The blended polyol and isocyanate are kept separate and recirculating.



Mix Head B

At shot time the cylinder is shifted so that the lower, feed line is open and the return line is closed as in the Mix Head B sketch. The two component streams are impinged on one another at high velocity, hence the name, an impingement mixer. The entire volume of material needed to fill the mold is injected in 4-6 seconds. The pressure in the feed lines can reach 2000psi as the components pass through the relatively small orifices into the chamber. In the flow channel and the mold the pressure drops to between 50 and 100psi making it possible to mold large parts with low tonnage presses or no press at all. The flow streams generate a great deal of turbulence that does a good job mixing the ingredients. A static mixer is often cut in the mold to be sure the mixing is complete.



Mix Head C

Once the shot is completely injected the mix head returns to the starting position, Mix Head C. The plunger has mechanically cleaned any mixed material from the chamber and the streams are redirected to the day tank.

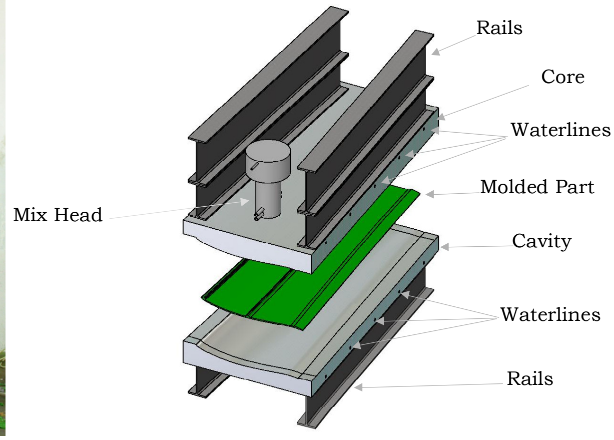
One of the questions that the trial molding answered was whether direct injection into a rib would create enough secondary mixing to cure completely. Release of the sprue used to feed the rib was another concern. The results were positive for both concerns. In spite of a bit of rough machining in the sprue, the sprue released with no problems. The rough undercuts will be removed when the full size molds are completed. We may also have the sprue coated with a teflon like coating, to enhance the long term release of the sprue from the mold.

- **Blade Design**

Before going into a discussion of the mold design and build process I will review the building of the blade model. LJM Consulting (LJM) created the aeronautical design for the blade using SolidWorks (see separate presentation on Automated Lofting for further details). SweetBriar (SB) used that model to create the upper and lower blade skins, also in SolidWorks. The whole blade was first truncated to remove the spar and then split into an upper and a lower piece. Joint detail was then added to the leading and trailing edges. The glue joint and interlocking features were not trivial and took a great deal more time than planned to complete. The blade is twisted for near optimum angle of attack at design tip speed ratio. When one projects a line onto the blade from a plane that represents the mold parting plane that line does not coincide with the end of the chord line. In order to avoid undercuts that could not be machined in the mold the projected line was used. This fact together with some discontinuities caused by LJM's automated routine made the leading and trailing edge features built by LJM unusable, and SB recreated them manually. Future versions of the lofting routine will be adjusted to remove the manual rework.

There were a number of open questions and uncertainties that needed to be addressed before we committed to the full size tooling. Initially we planned to make a smaller blade as a trial part or a skin for the trial part. Limited funds and cash flow interruptions made that plan unworkable so it was decided to proceed with a trial part that was a section of the full blade. This plan allows the team to answer some of the questions and do some testing of full sized bits prior to beginning the full tools.

We have completed the trial mold and are testing the skins that were made during the molding trial.



Here the painter has sprayed the cavity with the color coat in preparation for shooting the mold. On the right is a sketch of the mold for clarity.

The Molds

The Trial Mold

The trial molds make a 58" section of blade about midway out the airfoil portion of the blade.

SweetBriar used trimmed versions of the upper and lower skin models to create core and cavity blocks in SolidWorks. The 3D models were transmitted to Art Mold and Polishing in New Jersey, where they were imported into MasterCam to generate the CNC toolpaths used to cut blocks of aluminum into molds.

Funding interruptions and uncertainties during this phase of the project delayed delivery, threatened completion and strained long term relations with the vendor. These uncertainties and delays continue.

Molds for RIM parts are arranged in the press so that the appearance side of the part is down. (The appearance side, in trade terms, is the side that must be blemish free.) This is because the up facing side is where any bubbles from trapped air will form. In our case this meant the cores are located on the upper half of the mold, and since we wanted to feed the large rib in about the middle of the skin, the mixhead is mounted on the top half too.

Venting to allow the trapped air to escape as the molding material advances will be added when the full size mold has been made and sampled. Over flow channels to receive the vented material are cut into the bottom half of the mold. Once the sampling of the complete molds has been done the vents will be cut where needed. The venting will eliminate or greatly reduce the voids that appeared in the trial parts.

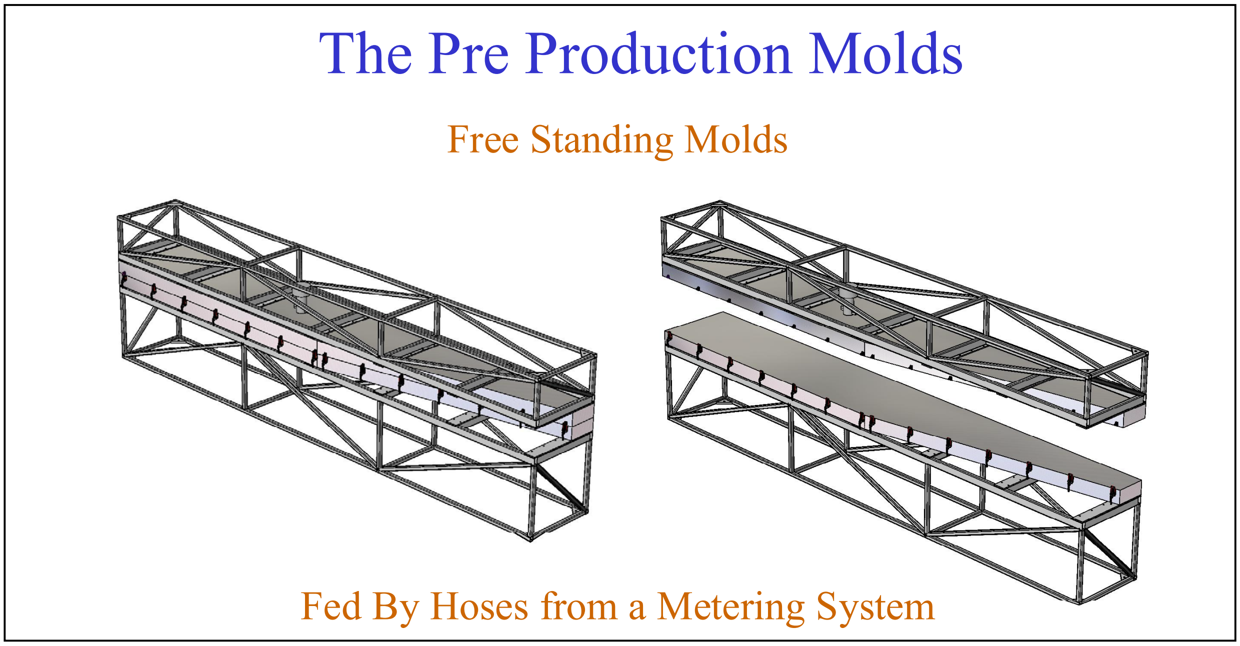
RIM molds require provision for controlling the mold temperature. Drilled water channels are the most common technique used. In production where rapid cycling is expected these lines are spaced about 3 inches apart and placed about 1.5 inches from the molding surface if possible. The blade molds will cycle at a leisurely rate so we used a greater distance between lines, however we have been careful to not place any mold details that would interfere with drilling lines on the tighter centers if those are later desired.

In order to remove parts from a mold ejection pins are often built. During design reviews with the material manufacturer and the molder we decided that these parts would not need any assistance demolding, so the ejector system was eliminated, saving considerable time and money. A waxy release agent is normally applied to the mold surface each cycle and this together with the simple, well-drafted shape made removal a straightforward process.

Should ejector pins have proved necessary SB had planned to use rods driven by air cylinders to assist extraction. Individual air cylinders or ganged pins driven by a cylinder are common practice. A knockout plate and pin retainer plate similar to that used in an injection mold is another common option. The presses used in RIM are much simpler than those used for regular high-pressure injection molding so the KO plate is either provided with air or hydraulic cylinders or is connected to the opposite mold half by chains that move the plate when the mold is opened. Primitive, but effective and low cost.

The presses used are typically arranged so that the lower platen can be shuttled out of the press. This allows better access to the mold for cleaning and spraying of release agent or colorcoat. The entire press can be tilted or, in trade lingo, "booked" to help the flow of material during fill and to help eliminate bubbles. Wear and tear on the systems that allow these motions make getting the bottom of the mold back in the exact place each time almost impossible. For this reason molds are built with robust alignment systems designed so that the cores are protected from damage but they do not bind when opened unevenly.

The parts pictured above give a sense of the size that can be run in available presses. Larger parts can be run as freestanding molds. I'll talk about these next.



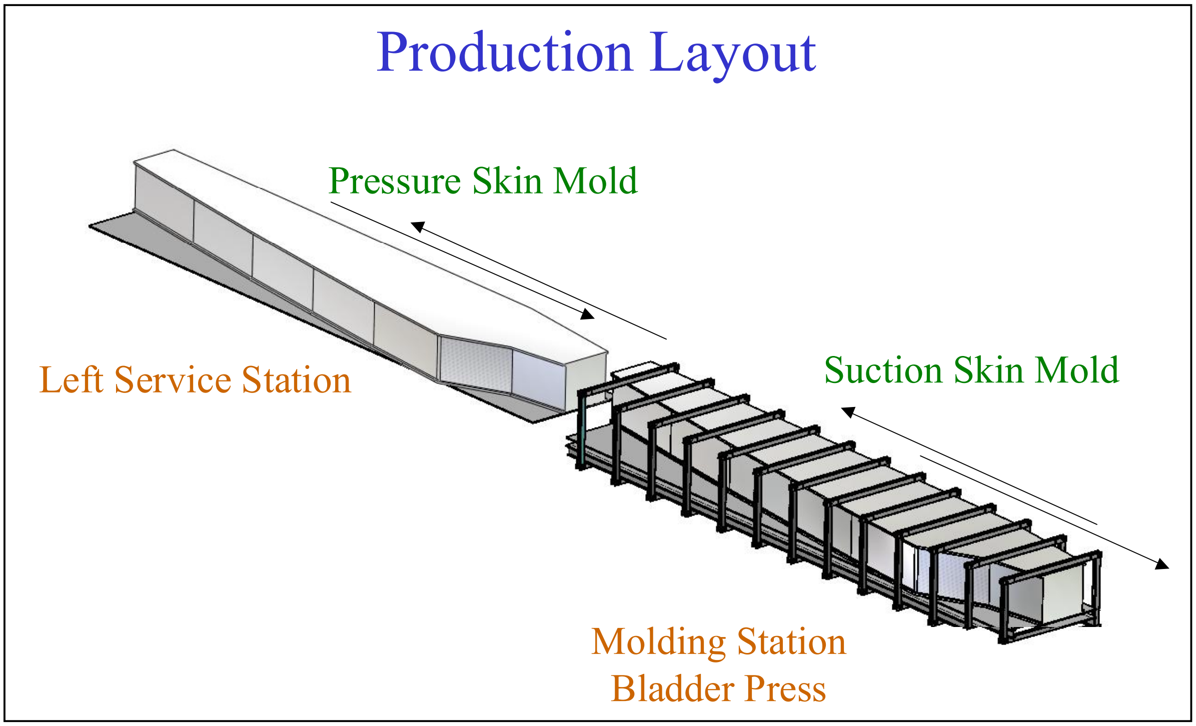
Preproduction Full Scale Tooling

The full-length blade molds are longer than the available presses so must be run as freestanding molds. The molds will be built in sections, which will be assembled on welded steel frames as shown above. For this program a single set of frames will be built and the molds swapped to save costs. The mold halves are held shut by toggle clamps, which are released to open the mold. The mold will be opened with a forklift or chainfall for the trials. In a low production run of a few tens or even hundreds of skins this method would be satisfactory. This arrangement will probably require 2.5 to 3.5 operators. (A half operator is someone shared by presses, such as a material handler or painter.)

The metered PU material would be fed to the mold with high-pressure hydraulic hoses. One could even set the system up with quick disconnect fittings so that a pair of molds could be run using the same (expensive) hoses. However the manpower requirements make that scenario unlikely.

The cycle time on a set-up like this is probably limited to 2 to 4 parts per hour and would likely be run on a single shift to ensure constant active supervision. As production ramped up it would make sense to replace the manual clamps with automatic ones.

There would come a point where cost pressure and production requirements would combine to force a more streamlined process, perhaps even one done in house. The next slide hints at a solution.



A High Production Layout

A bladder press in the middle is fed by two service stations, while a service crew demolds parts, cleans and prepares the mold at first one side then the other as the mold pair shuttles in and out of the press.

A system like this could produce astonishing numbers of blade skins per year at nearly unbelievably low cost compared to current methods. The capital costs are high but a strong case can be made when the demand volume is high enough to support high production levels.

Production Rates

- Cycle Time: 15 min. Close to close or 4 units per hour
  - Around the clock operation is typical
  - 4 shots per hour x 22 hr. (85% uptime) = 88 units a day
  - 3000 ÷ 88 = 34 days of production to cover a year's supply
- System can be idled to allow single shift operation or weekend shut-downs
- One metering system can feed more than one mold

Production Rates

The trial mold in a press was able to cycle in 6 minutes, which equates to 10 parts per hour. This rate is about as fast as the system will run, and is really only a good measure of the time needed to cure the part. A part as large as a 7.5m blade skin would not run this fast. It would take longer to remove the part and place it into cooling racks, painting the mold surface would take longer, as would spraying release agent on the core. The injection time for the PU material is really set by the reactivity of the resin system and could only increase a couple of seconds unless drastic reformulation were done to slow the reaction rate down.

The example in the slide above is fairly reasonable and a good place to start. Even with single shift operations the annual requirement for 1000 rotors can be manufactured in three months. That level of production is very attractive to a molder and borders on justification for building a dedicated plant.

The remaining slides showing costs were a necessary obfuscation to give the attendees a sense of the costs involved while protecting our proprietary interests. I was not satisfied with them and I suspect the listeners were not either, so here I will try another tack.

Mold Costs

First a look at the cost of machined aluminum molds compared to the FRP tooling common in the industry now. We were able to build the molds for about 3.5 times what a set of FRP tools cost by cutting costs at every step and choosing materials carefully. Our contract with the DOE is for a demonstration of feasibility rather than for production ready tooling. The molds will be the basis for a production tool set but the group will need to secure more funding to go into production. We are pursuing that funding.

Operational costs for the hard tools are much lower than comparable costs for soft tools. There is almost no damage done to the mold surface during normal molding operations. Some parting line damage can be expected due to manual scraping and flash removal. Welding and hand working the effected area can correct minor damage that affects the part. Parting lines in production molds survive 25 to 50 thousand cycles and with only a little extra care can last twice that many shots. Major damage like that caused by shutting the mold with a wrench in it does occasionally happen in a production facility but is often covered by insurance and is the responsibility of the molder not the mold owner.

Normal care consists of cleaning the mold and protecting the mold surfaces and waterlines from corrosion and physical damage. When not in use the molds are sprayed with a protective coating, closed and placed in dry storage. Sometimes in situations where the water used to control the temperature is hard or corrosive special treatments such as nickel plating is used.

Mold Costs for FRP Blade

- **Assume Present "Standard" Open Shell Halves Tooling:**
  - ⇒ Standard Matched FRP "Soft" Mold set cost is $Ref.
  - ⇒ Demand is 50 Rotors or 150 Blades per year (retrofit market)

- Unit cost share FRP = 100% of $Ref mold cost

- Life-span of Mold: 500 - 1000 blades
  - – And assuming careful maintenance, so mold life is:
  - √ 1,000 / 150 = 6.7 years

Very high annual maintenance costs: 10% per year
For standard FRP molds.

Baseline mold costs for a FRP tool set.

The important points to take away from this slide are, (1) the small number of blades (shots; in molding terms) a FRP mold is capable of producing and, (2) the high cost of maintaining the tool in a production ready state. These tools are not suited to volume production for at least two reasons, low output and high labor cost. Even at two shots a day these molds will produce fewer than 300 blades a year. I strongly doubt that any production facility using a single mold set reaches anywhere near that level of production.

Mold Costs for RIM Blade

- **Assume Low Production Rate**
  - ⇒ Mold set cost: 3.5*$Ref
  - ⇒ Hundreds of blades per year

- Unit cost share RIM(low rate) = 138% of $Ref mold cost

- Life-span of Mold: 25k - 50k shots
  - – And with careful maintenance that can double:
  - √ Lifetime of hundreds of years per mold!

Very low annual maintenance costs: a few hundred dollars per year
BUT absurd to think a single blade design could exist for even 5 yrs

RIM Mold costs for LOW Production rates make no sense.

High per unit costs for the hard tooling cannot be justifiable even with the low maintenance costs. The long tool life is of no advantage to the blade manufacturer. To produce a thousand blades on a three-shift basis would require 11.4 (1000 ÷ 88) days, running the molds in the same press one still makes the year's part requirement in less than a month. That is a lot of blades to deal with in a very short time frame and a lot of storage space while they await assembly into rotors and turbines.

Mold Costs for RIM Blade

- **Assume High Production Rate**
  - ⇒ Mold set cost:3.5 * $Ref
  - ⇒ Thousands of blades per year

- Unit Cost Share Rim(high rate) = 12% of $Ref mold cost

- Life-span of Mold: 25k - 50k shots
  - – And with careful maintenance that can double:
  - √ Mold lifetime of tens of years, even in high rate production!

Very low annual maintenance costs: a few hundred dollars per year
And very likely a single blade design could be useful for 8 years,
Given present turbine lifetimes are >20 years.

RIM Mold costs at HIGH production rates make a LOT of sense.

Once sales volume reaches a few hundred to a couple thousand rotors a year these costs begin to fall into line. As sales increase beyond that the case for hard tooling becomes increasingly more compelling.

Labor Cost Comparison

- Assume as above and find the burdened labor cost per blade:

⇒ Production rate:	4 units per hour	
⇒ Operators	1.5 labor hr/(4 blades/hr)	= 9% of $X
⇒ Fringe	1.5 fringe hr/ (4 blades/hr)	= 6% of $X
⇒ Machine rate	1 machine hr/ (4 blades/hr)	= 85% of $X
⇒ **RIM Blade**	**Direct & Indirect labor costs**	**= 100% of $X**

- Now find the burdened labor cost per blade for standard FRP blade:

⇒ Production rate:	1 unit per week	
⇒ Operators	80 labor hr/(1 blade/wk)	=1900% of $X
⇒ Fringe	80 fringe hr/(1 blade/wk)	= 1300% of $X
⇒ Facility rate	$25/hr x 40 hours	= 1700% of $X
FRP Blade	**Direct & Indirect labor costs**	**= 4900% of $X**

Labor Costs Comparison

This slide is a bit of an apples to ducks comparison since the processes are so different, however…

The point to assimilate here is the vast difference in the labor component. Labor is expensive, unreliable and its cost continues; once spent, the money paid for labor is gone. Hard tooling, on the other hand, lasts and continues to give a return. Over it's lifetime hard tooling becomes inexpensive in terms of per unit cost.

The more consistent production is an added benefit, further reducing production cost due to reduced scrap rates and improved assembly rates because of the molded in assembly features.

Molding Costs RIM Skin

More ducks versus apples.

The carbon spar and the polyurethane skins will end up weighing less than the FRP structure. It is really not possible to assign true costs to the skin portion of a traditional FRP blade such as the Aerostar blades, however spar and skin blades have been made from glass and carbon and the cost of that process is known.

The slow rate of production and high labor costs drive the cost of the FRP blade skins, material costs are also a significant factor. The material cost and tooling amortization drives Polyurethane skin costs. Labor is an almost insignificant factor compared to FRP blades. Their lighter weight contributes to lower manufacturing cost and also to lower operating costs through reduced drive component maintenance costs.

Total Blade Manufacturing Costs

- RIM mold amortization is **1.2% of standard frp blade cost** (high rate production)
- Carbon is more expensive than glass, but carbon spar is lighter, so material cost is about 50% of FRP blade cost
- Notional Blade Potential Manufacturing Cost Projection based on representative high rate production data to illustrate potential benefits

	FRP Blade	RIM/Carbon
– Blade Skin	46%	5%
– Amortization	8%	2%
– Spar	46%	43%
Total	**100%**	**50%**

SweetBriar Art Mold Corp Composite Engineering, Inc Blade Group Bayer plastek

Total Manufacturing Costs

Here we try to summarize without giving away any specific dollar information.

The RIM mold, amortized over a reasonable amount of production will still cost a bit more than will a FRP mold also over a reasonable production quantity. The RIM mold will produce far more parts in that reasonable production period so the cost per blade is significantly lower. Fewer pounds of a less expensive material plus much lower labor costs contribute to a lower skin cost. The spars come out fairly close with the carbon one having a slight edge in terms of cost.

The bottom line gives the possible outcome given the assumptions used. An impressive result, which is not unreasonable to expect if there is sufficient demand for the blades. We believe that that demand is there and that by being able to offer a range of different blade sizes built from a modular mold we can succeed in meeting that demand.

Appendix A
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WEBSITES

- www.rimmolding.com
- www.bayermaterialscience.com
- www.giplastek.com

SEARCH KEY WORDS

- RIM
- reaction injection molding
- polyurethane
- DCPD, dicyclopentadiene

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